Global impacts of energy demand on the freshwater resources of nations

Article (Published Version)

PNAS PLUS

Global impacts of energy demand on the freshwater resources of nations

Robert Alan Holland[a,1], Kate A. Scott[b], Martina Flörke[c], Gareth Brown[d], Robert M. Ewers[d], Elizabeth Farmer[e], Valerie Kapos[e,f], Ann Muggeridge[g], Jörn P. W. Scharlemann[e,h], Gail Taylor[a], John Barrett[b], and Felix Eigenbrod[a]

[a]Centre for Biological Sciences, University of Southampton, Highfield Campus, Southampton SO17 1BJ, United Kingdom; [b]Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, United Kingdom; [c]Center for Environmental Systems Research, University of Kassel, 34109 Kassel, Germany; [d]Department of Life Sciences, Imperial College London, Silwood Park Campus, Ascot SL5 7PY, United Kingdom; [e]United Nations Environment Programme World Conservation Monitoring Centre, Cambridge CB3 0DL, United Kingdom; [f]Department of Zoology, University of Cambridge, Cambridge CB2 3EJ, United Kingdom; [g]Department of Earth Science and Engineering, Imperial College, London SW7 2AZ, United Kingdom; and [h]School of Life Sciences, University of Sussex, Brighton BN1 9QG, United Kingdom

Edited by Dieter Gerten, Potsdam Institute for Climate Impact Research, Potsdam, Germany, and accepted by the Editorial Board September 18, 2015 (received for review April 21, 2015)

The growing geographic disconnect between consumption of goods, the extraction and processing of resources, and the environmental impacts associated with production activities makes it crucial to factor global trade into sustainability assessments. Using an empirically validated environmentally extended global trade model, we examine the relationship between two key resources underpinning economies and human well-being—energy and freshwater. A comparison of three energy sectors (petroleum, gas, and electricity) reveals that freshwater consumption associated with gas and electricity production is largely confined within the territorial boundaries where demand originates. This finding contrasts with petroleum, which exhibits a varying ratio of territorial to international freshwater consumption, depending on the origin of demand. For example, although the United States and China have similar demand associated with the petroleum sector, international freshwater consumption is three times higher for the former than the latter. Based on mapping patterns of freshwater consumption associated with energy sectors at subnational scales, our analysis also reveals concordance between pressure on freshwater resources associated with energy production and freshwater scarcity in a number of river basins globally. These energy-driven pressures on freshwater resources in areas distant from the origin of energy demand complicate the design of policy to ensure security of fresh water and energy supply. Although much of the debate around energy is focused on greenhouse gas emissions, our findings highlight the need to consider the full range of consequences of energy production when designing policy.

energy | freshwater | nexus | MRIO | sustainability

Meeting society's demand for fresh water and energy has been identified as a major challenge for society over the coming decades (1, 2). Most of the estimated 35 million km^3 of fresh water that exists globally is inaccessible (3). Recent estimates put renewable freshwater resources in the region of between 40,000 and 66,000 $km^3 \cdot y^{-1}$ (4, 5), of which ∼10% is appropriated for human use (6–8). Although this global total might be considered to fall within the "safe operating space" of humanity (9), it hides substantial mismatches between availability and demand in different regions (7, 8, 10) and associated pressures on renewable freshwater resources (1, 11). Given that freshwater is central to maintain ecosystem function (12) and biodiversity (13), pressures on freshwater resources can result in the loss of ecosystem services (14–16) and associated benefits to society, ultimately impacting human wellbeing both directly and indirectly (17–19).

Fresh water is used by the energy sector along the complete supply chain from extraction and conversion of raw material through to generation of power (2, 20), such that limits on access to fresh water through physical scarcity or regulatory control can have significant implications for security of energy supply (21). At the same time, energy is needed for extraction, treatment, and distribution of fresh water (2) to meet societal demand. This interdependence of fresh water and energy (2, 22–25) means that limits on one will impact the other, potentially causing significant economic, environmental, and social costs (23). Despite growing recognition of the importance of this water–energy nexus (26), policy objectives relating to fresh water and energy are often poorly integrated and concerned primarily with exploitation of fresh water and/or implications of climate change on freshwater resources required for energy production (27, 28). Indeed, alignment of climate and energy policy has led to the adoption of energy strategies that have the potential to negatively affect freshwater resources (25, 27).

A key difference between energy and fresh water is the relative ease with which the former can be transformed and transported between areas of production and demand (28). The resulting geographic disconnect between sources of inputs associated with energy production and final energy demand poses a significant challenge for resource management at the water–energy nexus. Countries can implement policies that improve energy and freshwater resource management within their own territories (23), with most developed countries exhibiting rapid reform of both sectors in recent years (26). However, movement of energy resources around the world, coupled with increasing trade in

SUSTAINABILITY SCIENCE

Significance

Understanding the role of international trade in driving pressures on freshwater resources is key to meeting challenges at the water–energy nexus. A coupled trade and hydrological model is used to examine pressures on freshwater resources associated with energy production across the global economy. While the electric and gas sectors induce freshwater consumption predominantly within countries where demand originates (91% and 81%, respectively), the petroleum sector exhibits a high international footprint (56%). Critical geographic areas and economic sectors are identified, providing focus for resource-management actions to ensure energy and freshwater security. Our analysis demonstrates the importance of broadening the discourse on energy policy to address issues including freshwater scarcity, the role of international trade, and wider environmental and societal considerations.

Author contributions: R.A.H., K.A.S., G.B., R.M.E., V.K., A.M., J.P.W.S., G.T., J.B., and F.E. designed research; R.A.H. and K.A.S. performed research; R.A.H., K.A.S., M.F., and E.F. analyzed data; and R.A.H., K.A.S., M.F., G.B., R.M.E., E.F., V.K., A.M., J.P.W.S., G.T., J.B., and F.E. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission. D.G. is a guest editor invited by the Editorial Board.

Freely available online through the PNAS open access option.

[1]To whom correspondence should be addressed. Email: r.a.holland@soton.ac.uk.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1507701112/-/DCSupplemental.

"virtual water" (29), adds complexity to the identification of policy and management options to ensure security of supply of both resources along global supply chains.

There is an increasing understanding that international trade in natural resources, driven by rising national wealth and the opening up of commodity markets since the 1980s, has led to a disconnect between final consumption of goods and production activities such as the extraction and processing of resources and associated environmental impacts (30). The implications of this disconnect have been explored predominantly for greenhouse gas emissions (31–34), but also for freshwater use (29, 35), land use change (36, 37), material use (30), and biodiversity (38). Consistent across these studies is a bias in environmental transfers in favor of net-importing developed nations at the expense of resource-exporting less developed nations. For example, emissions saved by industrialized countries bound by emissions reduction targets under the Kyoto Protocol were offset through emissions associated with the import of goods from countries without such emissions targets (34). There is considerable evidence to show that such carbon leakage can jeopardize climate targets (39) and that carbon-importing countries gain more socioeconomic benefits from international trade than carbon-exporting countries (40).

Such studies make a compelling case to incorporate the transfer of resources through international trade within national policies and sustainability assessments, so that the implications of consumption of goods for environment and society can be fully considered (30, 37). In the case of renewable freshwater resources, where impacts will be congruent with areas of resource extraction or production of goods, understanding and locating the geographic disconnect between use of fresh water and drivers of demand (29, 35, 41, 42) is key for assessing sustainability. In the present study, we investigate differences between energy sectors in the magnitude and geographical distribution of consumption of renewable freshwater resources, explore the geographical relationship between energy-induced freshwater consumption and the demand that drives it, and consider the implications in the context of freshwater scarcity. We use an empirically validated, environmentally extended multiregional input–output (EE-MRIO) approach that is spatially resolved at subnational scales. A spatially resolved, comprehensive analysis is vital, because energy-driven demand can be an important contributor to pressures on freshwater resources in localized regions (21, 43). Our analyses focus on freshwater consumption as this factor represents loss of the resource to the immediate environment (8) and so an opportunity cost in terms of ecosystem benefits (44). We do not consider freshwater withdrawal, which refers to fresh water removed from a source and used for human activity before being returned to the environment (8). Our analyses isolate freshwater consumption embodied in the three main energy sectors (gas, electric, and petroleum) globally, taking into account all processes along the supply chain from material extraction, transformation to energy carriers, and distribution to final consumers. Although a number of studies have examined the water–energy nexus at regional and national scales using EE-MRIO techniques (24, 45), ours is, to our knowledge, the first to attempt such an analysis at a global scale.

In the first stage of the analysis, a MRIO table derived from the Global Trade Analysis Project (GTAP; ref. 46) (*SI Appendix*, section 1) that quantifies economic transactions between 57 sectors across 129 countries/regions, is linked to data from the hydrological model WaterGAP that provides freshwater consumption data associated with agricultural, energy, domestic, and industrial activity (47–49) (*SI Appendix*, section 2). The environmental extension to the MRIO that this link provides allows us to reattribute direct sectorial freshwater consumption after the trade transactions to the final consumer of a finished commodity, a process known as footprinting (*SI Appendix*, section 3). The approach to this country/region-scale analysis is comparable to other studies that have examined international trade as a driver of pressures on freshwater resources (29) but which have not specifically addressed issues around the water–energy nexus. The second stage of analysis refines country/region values for freshwater consumption calculated in the EE-MRIO to subcountry/region scales (0.5- × 0.5-degree grid cell resolution) to describe spatial heterogeneity in freshwater consumption (35) (*SI Appendix*, section 4). This is a vital step, because locality is critical to determining the implications of freshwater consumption given the uneven distribution of renewable freshwater resources (7, 42). Based on this 0.5 × 0.5 degree grid cell resolution data, patterns of freshwater consumption associated with energy demand are considered within the context of available renewable freshwater resources in the world's river basins (4) to identify areas of critical importance for security of fresh water and energy supply (*SI Appendix*, section 6).

Results

Overview of Freshwater Consumption. Before presenting the results of the EE-MRIO analysis and considering freshwater consumption induced by the global energy sector from a consumption-based perspective, we provide a brief overview of the underpinning data to place our analysis within the wider context of freshwater consumption associated with human activity. Data from the WaterGAP model indicate that the crop sector dominates freshwater consumption, accounting for 91.85% (1,237 $km^3 \cdot y^{-1}$) of the 1,314 $km^3 \cdot y^{-1}$ of global annual freshwater consumption. This figure corresponds to findings in previous studies (35) that have emphasized agricultural production as the principal driver of pressures on freshwater resources globally. Industrial and domestic demand accounts for 5.88% (77 $km^3 \cdot y^{-1}$) of the remaining freshwater consumption, again corresponding to findings stated in ref. 35.

Of this industrial and domestic freshwater consumption, 23.78% (or 1.40% of global total freshwater consumption) is directly associated with the energy sectors considered in this analysis. Although this figure is comparatively small, the importance of considering freshwater consumption associated with energy sectors arises for two reasons. Firstly, freshwater consumption associated with energy extraction and refining may be highly locally concentrated and so contribute to social, environmental, and economic problems in specific regions (21)—a question we examine through our spatially explicit impact analysis. Secondly, our assessment employs EE-MRIO analysis to calculate the sum of embodied freshwater within all of the products required to meet final demand in isolated energy sectors. Thus, we identify not only freshwater consumption associated with specific energy sectors (e.g., oil extraction, oil refining, etc.), but also freshwater consumption associated with inputs required by these sectors (e.g., steel production for infrastructure and crops for biofuel) that could contribute to pressures on freshwater resources through higher intensities or in different geographic areas than the directly energy-related activities.

Country/Region Energy-Driven Freshwater Consumption Footprints. Our analysis finds that when measuring total freshwater consumption along global supply chains, the electricity sector consumes 6.48 km^3 of freshwater per year, with the petroleum sector consuming 1.60 $km^3 \cdot y^{-1}$ and the gas sector 0.30 $km^3 \cdot y^{-1}$. For each of the 129 countries/regions within the EE-MRIO, total freshwater consumption is disaggregated to describe the amount that occurs within the country/region where demand originates (i.e., territorial consumption) and the amount that is sourced internationally along energy supply chains (Fig. 1). The proportion of internationally sourced freshwater consumption is highest for activity induced by the petroleum sector (Fig. 1*A*), at 56% of total consumption for this sector. For the electricity (Fig. 1*B*) and gas (Fig. 1*C*) sectors, respectively, 9% and 19% of total sector-induced freshwater consumption is sourced internationally. For the

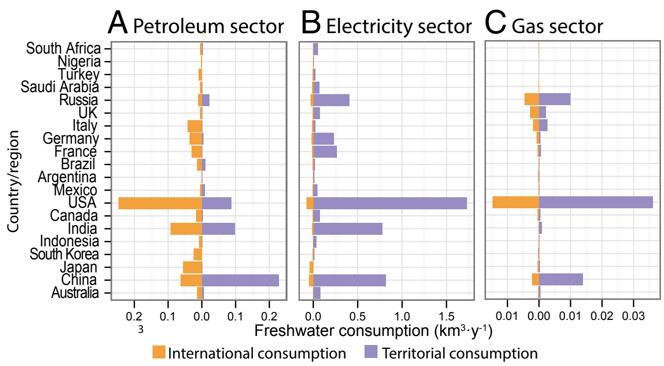

Fig. 1. Territorial and international freshwater consumption associated with petroleum (*A*), electricity (*B*), and gas sectors (*C*) for major economies [the G20, BRICS (Brazil, Russia, India, China, and South Africa), and MINTs (Mexico, Indonesia, Nigeria, and Turkey)]. An expanded version showing all countries/regions can be found in *SI Appendix*, Fig. S1.

petroleum sector as a whole, the largest consumers of fresh water are the United States (0.34 $km^3 \cdot y^{-1}$), China (0.29 $km^3 \cdot y^{-1}$), and India (0.19 $km^3 \cdot y^{-1}$). Together, these three countries account for 50% of total freshwater consumption within this sector. These countries exhibit markedly different patterns of territorial and international consumption (Fig. 1). For the United States, 73% of total freshwater consumption associated with the petroleum sector occurs internationally; this finding contrasts with China, where 22% occurs internationally, and India, where there is an almost even division (52% territorial and 48% international).

Given that the United States and China have comparable total freshwater consumption associated with their energy sectors (Fig. 1), we focus on the geographic and sectorial patterns of freshwater consumption of these two in further detail, while noting that the technique can be extended to all countries/regions (*SI Appendix*, Fig. S1). Countries and sectors have been aggregated for illustration purposes (Fig. 2), with the underlying analysis based on 129 countries/regions and 57 sectors (*SI Appendix*, section 3). Consistent with the patterns shown in Fig. 1, freshwater consumption by the petroleum sector in the United States is geographically diverse (Fig. 2*A*), occurring in northern America (27%), western Asia (29%), southern Asia (13%), eastern Asia (7%), and northern Africa (6%). This diversity contrasts with the Chinese petroleum sector (Fig. 2*B*), where 78% of freshwater consumption occurs within China, with the remainder occurring mainly in other Asian countries/regions (13%) and in eastern Africa (4%). The majority of freshwater consumption associated with the electricity (Fig. 2 *C* and *D*) and gas (Fig. 2 *E* and *F*) sectors for the United States and China is located within the territory where demand originates.

Utilization of goods or services along the supply chain of energy provision is reflected in the breakdown of freshwater consumption by sector of activity. For both the United States and China, the EE-MRIO demonstrates that the majority of freshwater consumed to produce petroleum (Fig. 2 *A* and *B*) is by the crop sector (76% and 44%, respectively), the electric sector (12% and 10%, respectively), the oil sector—relating to extraction of raw materials (2% and 16%, respectively), direct use in the petroleum sector itself (2% and 8%, respectively), and, to a lesser extent, sectors relating to industry (e.g., metal and machinery production) and services (e.g., insurance, banking, and other support services). A similar pattern is found for the gas sector (Fig. 2 *E* and *F*), with crops (71% and 37%, respectively, for the United States and China) dominating. In contrast, the majority of freshwater consumption by the electricity sector (Fig. 2 *C* and *D*) is associated with the sector itself (91% and 64%, respectively, for the United States and China), followed by crops (8% and 19%, respectively).

To illustrate the mechanism that drives the dominance of freshwater consumption associated with crops within energy sectors (Fig. 2), the EE-MRIO was used to describe how an increase in one unit (i.e., US$1) of output of the US petroleum sector induces production activities and corresponding freshwater consumption to support them (*SI Appendix*, section 3.2). For an increase in US$1 of output from the US petroleum sector, US$2.52 of economic activity is induced upstream in the global economy. This increase is associated with an additional 2,500 $m^3 \cdot y^{-1}$ of freshwater consumption. In economic terms, of the US$2.52 of induced activity, 31% is in the oil sector (extraction of materials), 45% in the petroleum sector itself (refining, distribution etc.), and 1% in crop production. Expressed in terms of freshwater consumption ($m^3 \cdot y^{-1}$), the 1% of additional economic activity in the crop sector accounts for 76% of the additional fresh

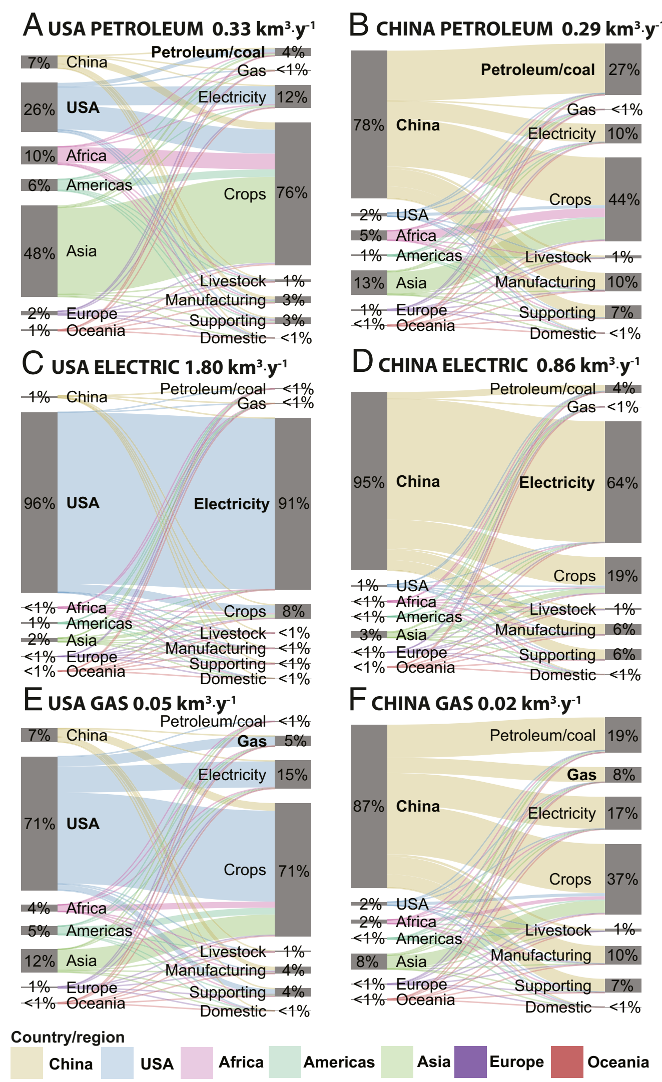

Fig. 2. Freshwater consumption by country/region and sector across three energy sectors. Sankey diagrams capture the relationship between the regional and sectorial consumption of freshwater driven by demand for petroleum products (*A* and *B*), for electricity (*C* and *D*), and for gas (*E* and *F*) in the United States (*A*, *C*, and *E*) and China (*B*, *D*, and *F*). Gray bars indicate percentage of total freshwater consumption by geographic region and sector. Colored lines describe the relationship between the region where demand originates and the sector within the region where freshwater consumption is occurring. See *SI Appendix*, Table S2 for details of country/region and *SI Appendix*, Table S1 for sector aggregation.

water consumed. This finding contrasts with induced activity in the oil and petroleum sectors, which drive only 4% of additional freshwater consumption, but accounts for three quarters of additional economic activity.

Subcountry/Region Energy-Driven Freshwater Consumption Footprints for United States and China. Using the approach of ref. 35, the global distribution of freshwater consumption associated with the individual energy sectors in the United States and China was mapped to 0.5- × 0.5-degree grid cells (Fig. 3; *SI Appendix*, Figs. S3 and S4). Data at the country/region scale were disaggregated based on intensity of freshwater consumption and location of economic activity within each 0.5- × 0.5-degree grid cell, corresponding to the economic sectors within the EE-MRIO (*SI Appendix*, section 4) to reveal spatial heterogeneity within countries/regions. Using the petroleum sector as an exemplar (Fig. 3) reveals a statistically strong correlation between geographic patterns of freshwater consumption for the United States (Fig. 3*A*) and China (Fig. 3*B*) ($r = 0.98$, F = 2776.78, df = 110, $P < 0.001$). This correlative relationship is likely driven by areas of common global resource extraction, manufacturing, and agricultural production across Asia, North Africa, Europe, and the Americas. However, there exist significant differences (*SI Appendix*, Table S6) between the United States (Fig. 3*A*) and China (Fig. 3*B*) in patterns of freshwater

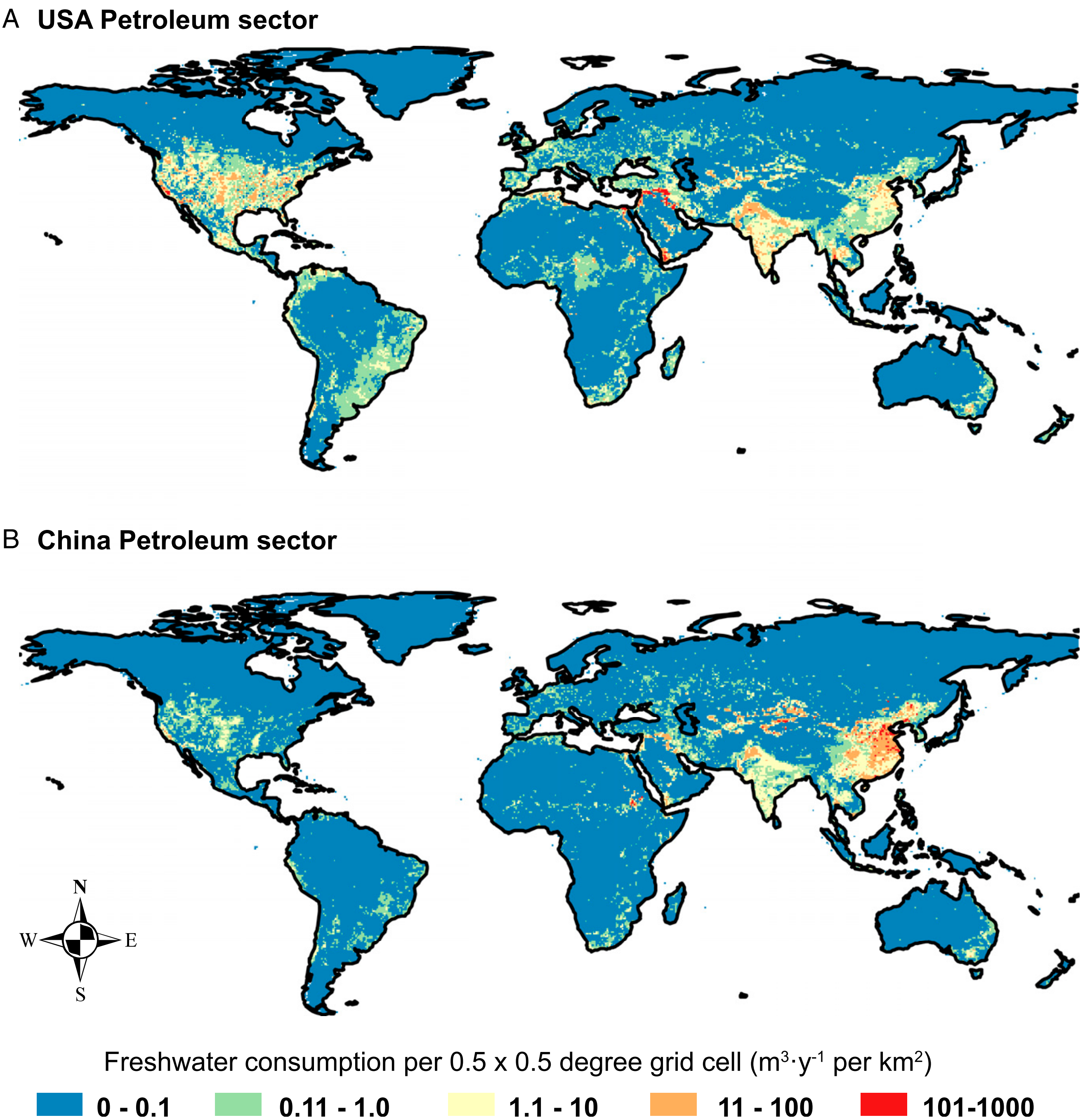

Fig. 3. Spatial pattern of global freshwater consumption driven by freshwater demand from the petroleum sector in the United States (*A*) and China (*B*). Numbers represent total freshwater consumption within each 0.5- × 0.5-degree grid cell standardized per unit area ($m^3 \cdot y^{-1}$ per km^2).

consumption in absolute terms driven by the higher international demand on freshwater resources associated with the US petroleum sector, as demonstrated at the country/region level (Figs. 1 and 2).

Implications of Freshwater Consumption. The implications of freshwater demand induced by energy sectors are dependent on the geographic overlap between location of activities required to meet demand (Fig. 3) and available freshwater resources (4). However, analyses of such relationships are complicated by the lack of a single universally accepted indicator with which to examine availability of freshwater resources (18) and the fact that impacts can arise through two mechanisms—first- and second-order water scarcity (50).

First-order scarcity represents a physical shortage of freshwater. Here we use two common metrics of first-order scarcity: (*i*) freshwater availability per person and (*ii*) the ratio of freshwater withdrawals to availability (18). We examine geographic concordance between these indices and aggregated freshwater consumption for the three energy sectors (petroleum, electric, and gas) for the United States and China. Bivariate mapping (*Materials and Methods* and *SI Appendix*, section 6) identifies common areas of spatial overlap between high freshwater consumption induced by the energy sector and river basins that can be considered to experience high first-order water scarcity based on thresholds proposed in the literature (18) (*SI Appendix*, Figs. S5–S8). An ensemble measure identifies major river basins in India, Pakistan, China, and the United States (Fig. 4) as being areas where energy-induced freshwater consumption is occurring within a context of high first-order water scarcity, irrespective of the metric used.

Second-order water scarcity arises through a lack of social adaptive capacity and reflects the economic and social context in which pressures on freshwater resources are occurring (50–52). The socioeconomic context can be as important as physical

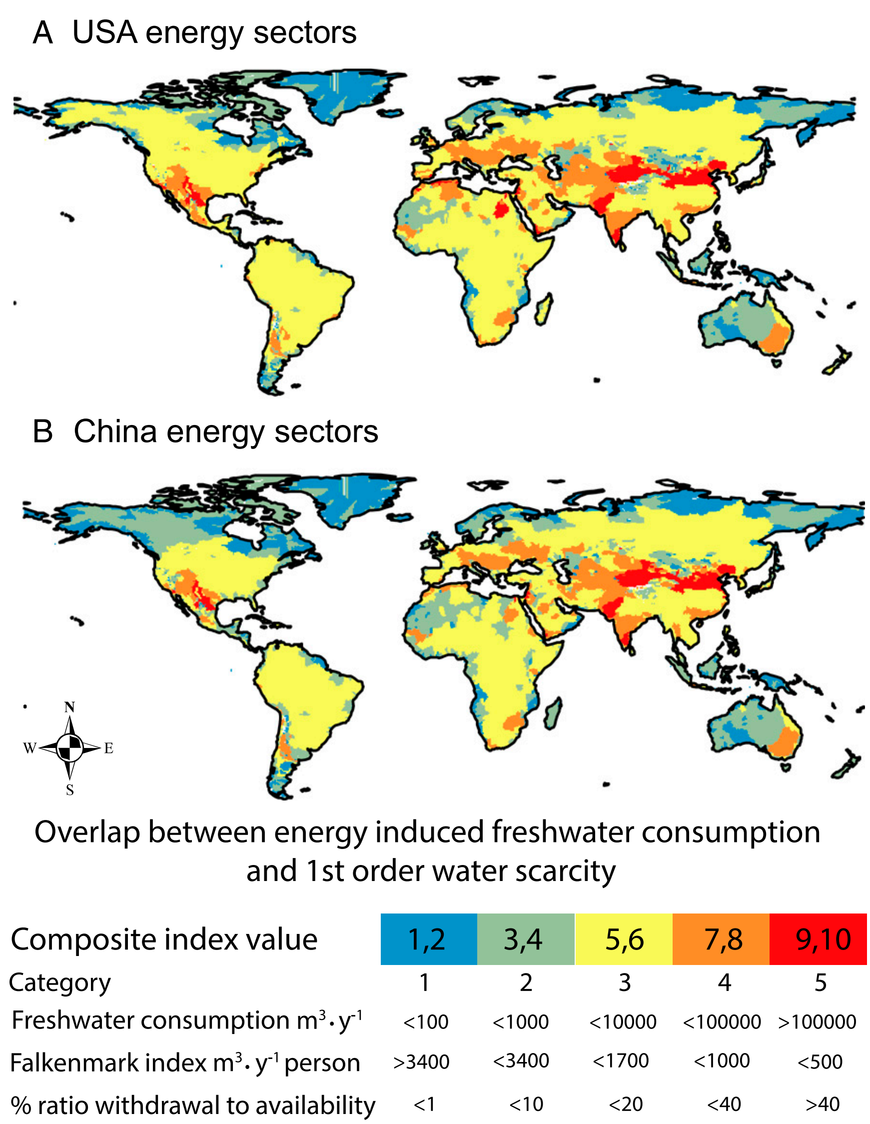

Fig. 4. Spatial relationship between freshwater consumption driven by demand for the US (*A*) and Chinese (*B*) energy sectors and pressures on freshwater resources. River basins were assigned to a category (1–5) based on freshwater consumption. This was combined independently with two measures of first-order scarcity assigned to categories (1–5) to produce two independent measures of overlap between energy-induced freshwater consumption and first-order scarcity. The mean of these independent measures represents a composite index value of coincident energy-induced freshwater consumption and first-order water scarcity (*Materials and Methods* and *SI Appendix*, section 6). High values (orange and red) indicate spatial overlap between river basins where high energy-induced freshwater consumption is occurring within a context of high first-order water scarcity.

scarcity in determining implications for society of pressures on freshwater resources (18, 52). Various approaches to calculate a "Water Poverty Index" reflecting second-order scarcity have been suggested (50, 51); however, varying availability of socioeconomic data at subcountry/region scale limits their application in the current study.

We examine second-order water scarcity using two indices (*SI Appendix*, section 6) that provide socioeconomic indicators at differing spatial scales. The Human Development Index (HDI) is a multidimensional measure that captures a range of social and economic factors that could influence second-order water scarcity and has been used in previous studies that considered social adaptive capacity and freshwater resources (52, 53). Using this national scale measure, we find no correlation between HDI and freshwater consumption associated with the energy sector for the United States (rho = −0.01, df 119, $P > 0.05$) or China (rho = 0.03, df 119, $P > 0.05$) globally. However, spatial mapping suggests overlap between countries where high energy-induced freshwater consumption is occurring within the context of low and medium values for the HDI (*SI Appendix*, Figs. S10 and S11) in India, Pakistan, China, and parts of the Middle East.

Our second indicator provides data on the prevalence of child malnutrition at a 0.5- × 0.5-degree grid resolution and has been used in a previous study (54) as a measure of social adaptive capacity. Indicators of human health such as malnutrition have been used in a number of studies examining pressures on freshwater resources (53, 55) because, together with economic and social factors, they represent facets relevant to understanding social adaptive capacity (51, 52, 56) and therefore second-order scarcity. As with national scale analysis, the lack of correlation between energy-induced freshwater consumption and our indicator of social adaptive capacity (prevalence of child malnutrition) for both the United States ($r = 0.01$, F 0.01, df 43.70, $P > 0.05$) and China ($r = -0.01$, F 0.0045, df 40.47, $P > 0.05$) results from the complex spatial relationship between the two. This relationship is revealed by using bivariate mapping at subnational scales, where areas of high energy-induced freshwater consumption are demonstrated to be occurring within the context of low social adaptive capacity within India, Pakistan, Southeast Asia, Northeast Africa, and parts of the Middle East (*SI Appendix*, Figs. S12 and S13). The two independent metrics (i.e., HDI and prevalence of child malnutrition) are therefore consistent in identifying a number of geographic regions where energy-induced freshwater consumption is occurring within a context of low social adaptive capacity, potentially contributing to second-order water scarcity.

Considered in the context of first-order scarcity (Fig. 4; *SI Appendix*, section 6), there is spatial concordance between geographic areas experiencing high levels of first-order (physical-driven) (Fig. 4; *SI Appendix*, Figs. S5–S8) and second-order (socioeconomic-driven) (*SI Appendix*, Figs. S12 and S13) water scarcity and highest energy-induced freshwater consumption in a number of river basins, notably in India and Pakistan (*SI Appendix*, section 6).

Discussion

Differences between countries in terms of the degree to which energy-induced freshwater consumption (Fig. 1) is derived from international sources have important implications for management of renewable freshwater resources. For countries such as China, where energy-induced freshwater consumption is largely sourced internally, there is a direct incentive to manage pressures on freshwater resources to ensure security of energy and freshwater supply. Pressures on freshwater resources, of which energy production represents one facet, are increasingly recognized by the Chinese government as a critical issue affecting human wellbeing, economic development, and national security within the country (57–59). Country-focused analysis using EE-MRIO techniques has demonstrated the physical and virtual transfer of freshwater resources between Chinese provinces to support economic activity (60, 61). In demonstrating that globally driven demand for freshwater resources, in this instance associated with energy sectors, contributes to pressures on freshwater resources within countries/regions far removed from where final demand lies our analysis compliments these findings (60, 61). Patterns of freshwater stress across China detailed by ref. 60 correspond to areas identified in our subnational scale analysis as being where demand induced by energy sectors is occurring within the context of high first-order scarcity (Fig. 4).

In contrast to China, for certain countries/regions and energy sectors (e.g., US petroleum sector), consumption of fresh water along complex international supply chains (35, 62, 63) complicates the development of policy responses and management options at the water–energy nexus. Territorial pressure on freshwater resources has been identified by the US government as a threat to energy security (64), a result supported by regional US analysis (25). However, our analyses demonstrate that the US petroleum sector is reliant on economic activity in countries/regions of the world that are exposed to significant pressures on renewable freshwater resources (e.g., India, Pakistan; Fig. 4) and where it may be difficult to implement the necessary market reforms (29) to safeguard freshwater resources. This finding is of particular relevance for activity in transboundary river basins such as the Indus, identified as an area of India and Pakistan associated with high energy-induced freshwater consumption occurring in the context of both first-order (Fig. 4) and second-order (*SI Appendix*, Figs. S12 and S13) water scarcity. Consideration of the water–energy nexus must be in terms of both the territorial and international demand for freshwater resources to enhance both our understanding of the security of energy supply, and broader issues of sustainability through the link between freshwater resources, human wellbeing, and economic development.

Findings in the present study can be placed within an emerging body of literature that suggests an imbalance in the use of natural resources (29, 30, 65–67) with exchanges between developed and less-developed countries having become increasingly ecologically unequal. The analysis of virtual freshwater transfers to affluent eastern provinces of China from other provinces in ref. 60 highlights that such an imbalance in resource use can also occur within countries. To address such transfers, ref. 60 suggests a number of policy mechanisms based on shared producer and consumer responsibility (68) that could be implemented and used to fund agricultural and industrial freshwater efficiency programs. In the context of findings in the present study, we would suggest that such mechanisms could also be used at the global level to ensure both the security of energy supply in areas where final demand lies and to address social, economic, and environmental issues where freshwater consumption to meet this demand originates. Ultimately, as argued by refs. 25 and 69, the analysis presented here provides information that can be used by policy makers to identify critical sectors and geographic regions at the water–energy nexus. When developing energy policy, decisions can then be made to invest in protecting these critical points to reduce social, environmental, and economic burdens. For example, in the 1970s, the government of Saudi Arabia identified threats to territorial freshwater resources as a major issue for the oil industry, such that the industry is now based almost entirely on the use of desalination technology and brackish water (70), a fact reflected in our analysis which finds comparatively low freshwater consumption in this region. Our analysis provides information that could enable transfer of resources between countries to enable similar sectorial changes to protect freshwater resources and ensure security of the energy supply.

Demand associated with each energy sector generates a long chain of interactions in its production processes because all of the resources—the material feedstock and energy inputs, the infrastructure requirements (factories, machinery, processing equipment, transportation, worker canteens etc.), the financial services used, and so on—need to be "produced" and in turn themselves require numerous inputs. The use of EE-MRIO therefore provides a different perspective on freshwater consumption that moves beyond considering a single aspect of energy production (e.g., petroleum refining or electric generation) to incorporate understanding of the inputs required to undertake such activity. Generation of each input consumes freshwater in the process, with the amount of consumption varying dependent on how freshwater-intensive the sector is, such that there can be large disparities between economic activity within a sector and the associated freshwater consumption. In breaking down energy sectors using EE-MRIO (Fig. 2), it is possible to identify in which inputs most freshwater consumption is embodied and thus consider strategies to reduce overall freshwater consumption by targeting specific sectors.

Across energy sectors, our analysis demonstrates that agricultural production represents a major contributor to total freshwater consumption (Fig. 2). The dominance of agriculture within our analysis (Fig. 2) is a reflection of high levels of freshwater consumption associated with crop production (35) that subsequently flows to energy sectors, as opposed to a high input of crop materials themselves. This finding was demonstrated in the analysis of the US petroleum sector in terms of both induced economic activity (US$) and freshwater consumption ($m^3 \cdot y^{-1}$). This result is also consistent with analysis that compares sectorial water footprint results across bottom-up (process based) and top-down (EE-MRIO) methods (71), finding substantial differences in water footprints in agricultural and industry sectors depending on the method used. These differences arise as EE-MRIO calculates the full supply chain water demands of final energy consumption, and hence it does not just sum the direct water consumption associated with only those supply chain components deemed important, as is the case in bottom-up approaches. As a result, ref. 71 demonstrates that, by using EE-MRIO, a higher proportion of a nations water footprint will be attributed to industry rather than crops and livestock, because a large proportion of agricultural water use is consumed by industrial sectors as production inputs (e.g., biofuel feedstock). *SI Appendix*, section 5 provides an overview of the different approaches to water footprinting.

Analysis based on MRIO therefore provides a complimentary perspective on freshwater consumption to bottom-up approaches that has a number of implications relevant for policy. Firstly, although transfer of technology and expertise between countries relating to the industrial side of energy production has a role to play in relieving pressures on renewable freshwater resources, particularly at point localities (e.g., industrial plants or power station), large gains could also be achieved in relation to agricultural production. Adoption of precision irrigation techniques and new crop varieties could represent a "soft path" to addressing pressures on renewable freshwater resources focused on improvements in efficiency (72) that would complement those already adopted on the industrial side of energy production. For example, ref. 73 demonstrates that reducing freshwater consumption of global crop production to a level that represents the top 25th percentile of current production values could deliver 39% freshwater savings compared with current levels of consumption. In the context of the present analysis, such savings would cascade through the global economy, reducing pressures on renewable freshwater resources associated with demand for crops driven by the energy sector (Fig. 2) and delivering benefits to the environment and society. It is not our purpose to propose the most effective form of governance, but, rather, to inform the debate encompassing those promoting market-based mechanisms and the monetary valuation of ecosystem services, to those advocating more collective and deliberative forms of local-level governance (74, 75).

Secondly, the importance of agriculture as a driver of freshwater consumption has implications associated with production of energy from biofuel feedstocks, suggesting that even modest increases in biofuel production, driven by recent US and European mandates, could displace freshwater consumption associated with food production to that associated with the energy sector. This finding is consistent with scenarios produced by the International Energy Agency that project an 85% increase in freshwater consumption associated with energy between 2010 and 2035, driven primarily by expanding biofuel production (21), and results presented in ref. 25 that demonstrate the impact on freshwater resources of increased reliance on bioethanol in California as a result of changes in energy policy since 1990. Such findings emphasize the importance of the spatial aspect of EE-MRIO (29, 35) as such information will allow policy to target feedstock production toward countries/regions based on availability of renewable freshwater resources and local socioeconomic conditions (42), thus contributing to sustainable production.

Although our analysis advances our understanding of the relationship between energy production and freshwater resources, there are nonetheless a number of limitations and improvements that require future research. Many of these limitations are common to EE-MRIO analysis; Daniels et al. (42) provide a detailed discussion specific to freshwater resources. Of these limitations, aggregation error, which refers to a lack of product specificity within sectors and to the grouping of countries into regional blocks (29, 42), will most significantly affect our findings in relation to subcountry/region-scale mapping of industrial activity. Our estimates of freshwater consumption within a specific sector assume homogeneity in levels of freshwater use efficiency that may mask distinct differences in spatial patterns associated with different industrial processes. A second limitation of our analysis is that total freshwater consumption at the country/region level is assigned to individual 0.5- × 0.5-degree grid cells in proportion to the location of industry and intensity of freshwater consumption within the grid cell, without taking account of distinct subcountry/region patterns that may be associated with individual supply chains. For example, although freshwater consumption in the electricity sector is defined spatially based on the location and type of power stations (48), our analysis treats electricity as a pooled resource. In reality, within a specific country/region, colocation of electric production and industry may mean that a higher proportion of generated electricity is being used for industrial process in some areas, and a higher proportion for domestic use in others. A third limitation is that for any future analysis using our methodology, the expected rapid expansion of second-generation bioenergy feedstocks will need to be incorporated both with the MRIO table through disaggregation of agricultural sectors and within the crop models contained within WaterGAP.

In addition to the EE-MRIO–specific limitations discussed above, an additional limitation to our analysis relates to understanding the relationships between pressures placed on renewable freshwater resources and the implications such pressures have for individuals and communities. Difficulties in the construction of indicators that reflect pressures on renewable freshwater resources arise through the wide range of environmental, economic, and social factors that interact to contribute to freshwater scarcity (18, 51). Our analysis addresses this challenge by using a range of possible indicators relevant to both first- and second-order water scarcity (Fig. 4; *SI Appendix*, section 6 and Figs. S10–S13) to identify concordance between regions with high freshwater scarcity and consumption associated with energy sectors. However, the relative coarse scale of our analysis (0.5- × 0.5-degree grid; river basin; country/region) and difficulty in obtaining data of relevance for understanding second-order water scarcity limit our ability to understand this relationship. Nevertheless, we identify coincident locations of demand for freshwater resources associated with energy sectors and areas subjected to high first- and second-order scarcity, notably in India and Pakistan. In such areas, analysis indicates that demand induced by energy sectors is occurring within a context of both physical freshwater scarcity and low social adaptive capacity to address the challenges that freshwater scarcity poses for human wellbeing and economic development. This finding provides the information necessary to conduct targeted studies along critical supply chains and channel investment and expertise to address pressures at local scales.

Our analysis lies at the interface of global efforts to meet societal energy and freshwater needs while addressing climate change. By demonstrating the global connectedness of the energy system and demands on freshwater resources that can be far removed from where final energy demand resides, we provide decision-makers with a key piece of knowledge to address future energy security, while at the same time considering social, environmental, and economic consequences of decisions. Given rising populations and the critical interdependence of freshwater, food, and energy demand, our work examines an important threat for global freshwater resources that has not previously been considered in detail. The fossil-based sector represents a major contributor to increasing atmospheric CO_2 (76), and as such strategies to reduce greenhouse gas emissions form the dominant discourse within energy policy. We argue that energy policy should increasingly be designed to incorporate not only implications for greenhouse gas emissions, but also consideration of other consequences that will affect global ecosystems and the goods and services that flow from them to society. Failure to do so may mean that we address climate change at the expense of existing natural resources on which human wellbeing and economies depend.

Materials and Methods

Country/Region Freshwater Consumption Footprints. The freshwater resources embodied in a country's/region's consumption are calculated by using EE-MRIO analysis (*SI Appendix*, section 3.1). EE-MRIO analysis is well suited to calculating consumption-based environmental accounts at the national and supranational level (42, 63, 77) because it enables trade flows across the full supply-chain of product categories traded globally to be linked to non-economic measures such as freshwater consumption.

The MRIO is based on data from GTAP (78), which is constructed from 2007 global economic data and contains domestic and international monetary transactions among 57 industry sectors across 129 countries/regions (*SI Appendix*, section 1). Our analysis focuses on three of these sectors—electricity, gas, and petroleum—because these sectors represent major sources of energy for the global economy. These three represent the sectors in GTAP in which raw materials are transformed into energy carriers that then flow to end users. For example, the GTAP petroleum sector (as used in this analysis) receives inputs from the GTAP oil sector, with the latter relating to activity associated with extraction of raw materials (e.g., crude oil). Refined products from the petroleum sector are then sold to industry and final consumers (e.g., goods manufacturers, services, and households).

Sectorial freshwater consumption by country/region derived from the hydrological model WaterGAP (4, 47–49) (*SI Appendix*, section 2) provides an environmental extension to the MRIO model following the method given in ref. 79. Freshwater consumption data for 19 crop and 12 livestock sectors were derived from WaterGAP, with details of the development of the WaterGAP irrigation and livestock models and assumptions provided in refs. 49 and 80. These data were aggregated into the eight crop and two livestock sectors in the MRIO model for each country/region by allocating these to the corresponding sectors (*SI Appendix*, section 3). Freshwater consumption associated with electricity production in WaterGAP (48) was allocated to the corresponding country/region electricity sectors in the MRIO. WaterGAP allocates all other (i.e., excluding crops, livestock, electricity, and domestic) freshwater consumption into a single "industry" sector, which represents 4.18% of total freshwater consumption within the EE-MRIO (47, 48). To disaggregate this industry sector among sectors not yet assigned a freshwater consumption value, country/region totals for industry in the WaterGAP model are apportioned among the industry sectors in the MRIO based on their expenditure on the water sector. Here, the strength of the interaction with the GTAP water sector is taken as indicative of differences in freshwater consumption between the GTAP sectors (6). Water prices between countries are considered; however, the price of water within a country is assumed to be constant, because no within-country price data were available. Data validation for key industrial sectors was also performed against industry and modeling figures from the literature (*SI Appendix*, section 3.3).

Freshwater directly consumed by industry sectors is reallocated through supply chains to the finished products in which it becomes embodied using the standard input–output equation originating from Leontief (81) (*SI Appendix*, section 3.1) and used by many in footprint analysis (for example, see refs. 29, 30, 42, and 61). Total freshwater consumption for an individual country/region is the sum of embodied freshwater along these supply chains to meet absolute demand for finished products. Sectorial consumption is determined by the country/region's demand for a specific product, such as electricity or petroleum. The embodied freshwater can be traced back to the sector and country/region in which it was originally extracted from the environment to determine the location of appropriation for the consumption activity.

Subcountry/Region Energy-Driven Freshwater Consumption. Country/regional patterns of freshwater consumption were mapped to 0.5- × 0.5-degree grid cells by using the approach described in refs. 35 and 48. Country/region totals for freshwater consumption in each sector were derived from the EE-MRIO. Values for intensity of freshwater consumption associated with crops and livestock (49, 80), electricity (48), and dwellings (47) were derived from WaterGAP at the 0.5- × 0.5-degree grid cell resolution. Country/region totals from the EE-MRIO were then assigned to each 0.5- × 0.5-degree in proportion to the intensity of freshwater consumption for the corresponding sector within that 0.5- × 0.5-degree grid cell derived from WaterGAP. Because of aggregation of the industry sector within WaterGAP (48) outlined above, this approach was modified by initially using data from a range of sources (*SI Appendix*, section 4) to identify 0.5- × 0.5-degree grid cells in which activity associated with key industrial processes (e.g., mineral extraction and refining, oil extraction) was located. Freshwater consumption at the country/region level for the corresponding sector was assigned to each of this subset of 0.5- × 0.5-degree grid cells in proportion to intensity of freshwater consumption associated with industry derived from WaterGAP (47, 48). Finally, the remainder of freshwater consumption associated with industrial processes was assigned to each 0.5- × 0.5-degree grid cell based on aggregate industrial freshwater consumption derived from WaterGAP (47, 48), after accounting for that already assigned in the previous step. Correlations between patterns of freshwater consumption between the United States and China were assessed by using a modified *t* test to account for spatial autocorrelation (*SI Appendix*, section 4.1).

Implications of Freshwater Consumption. Freshwater consumption associated with the United States and China energy sectors mapped to a 0.5- × 0.5-degree grid resolution (Fig. 3; *SI Appendix*, Fig. S3) was aggregated to river basins as defined by the WaterGAP model. Patterns of first-order water scarcity within each river basin were assessed by using two common measures: (*i*) the Falkenmark water stress indicator (18), which measures freshwater availability per person (*SI Appendix*, Figs. S5 and S7); and (*ii*) the percentage ratio of total freshwater withdrawals to availability (18) (*SI Appendix*, Figs. S6 and S8). In both cases, freshwater availability was defined as the total renewable freshwater resources derived from the WaterGAP model (4). To create an ensemble measure based on these two indices, firstly total freshwater consumption associated with the US and China energy sectors was categorized from low (category 1) to high (category 5) by using a logarithmic scale (*SI Appendix*, Figs. S5–S8). Secondly, each basin was assigned to a first-order water scarcity category from low (category 1) to high (category 5) based on proposed thresholds for each of the indices (*SI Appendix*, section 5; ref. 18; *SI Appendix*, Figs. S5–S8). For the Falkenmark water stress indicator, thresholds for freshwater scarcity were taken from ref. 18 such that (*i*) river basins with <1,700 $m^3 \cdot y^{-1}$ per person are considered to experience water stress; (*ii*) river basins with <1,000 $m^3 \cdot y^{-1}$ per person are considered to experience water scarcity; and (*iii*) river basins with <500 $m^3 \cdot y^{-1}$ per person are considered to experience absolute scarcity. For the water resources vulnerability index using thresholds taken from ref. 4, a river basin can be considered as: (*i*) water scarce if the percentage ratio of withdrawals to availability is between 20% and 40%; and (*ii*) severely water scarce if the percentage ratio of withdrawals to availability is >40%. Thirdly, the score for total freshwater consumption associated with the energy sector (category 1–5; *SI Appendix*, Fig. S9) was combined with each of the first-order water scarcity indicators (category 1–5; *SI Appendix*, Fig. S9) independently to calculate an index of coincident energy-induced freshwater consumption and first-order water scarcity. A river basin with high energy-induced freshwater consumption (category 5) and high first-order scarcity (category 5) would score the maximum of 10 on this coincident index (*SI Appendix*, Figs. S5–S8). Finally, an ensemble measure was calculated by taking an average score of the index of coincident energy-induced freshwater consumption and first-order water scarcity calculated from the two indices (Fig. 4; *SI Appendix*, section 6).

Second order scarcity was examined using two proxy indices for social adaptive capacity, the HDI at country/region scale and prevalence of child malnutrition at 0.5 × 0.5 degree grid resolution (*SI Appendix*, section 6). Correlation between these two indices at country/region level ($r = -0.75$, df = 118, $P < 0.001$) suggests that data on the prevalence of child malnutrition, which capture within country/region heterogeneity, is indicative of patterns revealed by the HDI which represents a more complex view of social adaptive capacity based on social, economic and health factors. Bivariate mapping was used to identify areas of coincident low adaptive capacity and high energy induced freshwater consumption associated with the United States (*SI Appendix*, Figs. S10 and S12) and China (*SI Appendix*, Figs. S11 and S13), for both HDI and prevalence of child malnutrition. Spatial overlap between river basins identified in the context of high first and second order stress and high energy induced freshwater consumption were assessed visually due to difference in spatial scale of data (*SI Appendix*, section 6).

ACKNOWLEDGMENTS. We thank Marco Sakai (University of Leeds) for his help compiling the multiregion input–output table from the GTAP database, and two anonymous reviewers for insightful comments. This work was supported through UK Energy Research Centre (UKERC) Project NE/J005924/1, "A Global Framework for Quantifying the Ecosystem Service Impacts of Oil and Biofuel Production." IHS provided high-quality global Exploration and Production and Midstream data at no cost for this global energy research.

1. Gleick PH, Palaniappan M (2010) Peak water limits to freshwater withdrawal and use. *Proc Natl Acad Sci USA* 107(25):11155–11162.
2. Gleick PH (1994) Water and energy. *Annu Rev Energy Environ* 19(1):267–299.
3. Shiklomanov IA (2000) Appraisal and assessment of world water resources. *Water Int* 25(1):11–32.
4. Müller Schmied H, et al. (2014) Sensitivity of simulated global-scale freshwater fluxes and storages to input data, hydrological model structure, human water use and calibration. *Hydrol Earth Syst Sci* 18(9):3511–3538.
5. Haddeland I, et al. (2011) Multimodel estimate of the global terrestrial water balance: Setup and first results. *J Hydrometeorol* 12(5):869–884.
6. Chen Z-M, Chen GQ (2013) Virtual water accounting for the globalized world economy: National water footprint and international virtual water trade. *Ecol Indic* 28: 142–149.
7. Oki T, Kanae S (2006) Global hydrological cycles and world water resources. *Science* 313(5790):1068–1072.
8. Gleick PH (2003) Water use. *Annu Rev Environ Resour* 28(1):275–314.
9. Rockström J, et al. (2009) A safe operating space for humanity. *Nature* 461(7263): 472–475.
10. Haddeland I, et al. (2014) Global water resources affected by human interventions and climate change. *Proc Natl Acad Sci USA* 111(9):3251–3256.
11. Vörösmarty CJ, et al. (2010) Global threats to human water security and river biodiversity. *Nature* 467(7315):555–561.
12. Woodward G (2009) Biodiversity, ecosystem functioning and food webs in fresh waters: Assembling the jigsaw puzzle. *Freshw Biol* 54(10):2171–2187.
13. Dudgeon D, et al. (2006) Freshwater biodiversity: Importance, threats, status and conservation challenges. *Biol Rev Camb Philos Soc* 81(2):163–182.
14. Dodds WK, Perkin JS, Gerken JE (2013) Human impact on freshwater ecosystem services: A global perspective. *Environ Sci Technol* 47(16):9061–9068.
15. Dudgeon D (2010) Prospects for sustaining freshwater biodiversity in the 21st century: linking ecosystem structure and function. *Curr Opin Environ Sustain* 2(5):422–430.
16. Brauman KA, Daily GC, Duarte TK, Mooney HA (2007) The nature and value of ecosystem services: An overview highlighting hydrologic services. *Annu Rev Environ Resour* 32:67–98.
17. Luck GW, Chan KM, Klien CJ (2012) Identifying spatial priorities for protecting ecosystem services. *F1000 Res* 1:17.
18. Rijsberman FR (2006) Water scarcity: Fact or fiction? *Agric Water Manage* 80(1–3): 5–22.
19. Horwitz P, Finlayson CM (2011) Wetlands as settings for human health: Incorporating ecosystem services and health impact assessment into water resource management. *Bioscience* 61(9):678–688.
20. Fthenakis V, Kim HC (2010) Life-cycle uses of water in U.S. electricity generation. *Renew Sustain Energy Rev* 14(7):2039–2048.
21. International Energy Agency (2012) *World Energy Outlook* (International Energy Agency, Paris).
22. Elcock D (2010) Future U.S. water consumption: The role of energy production. *JAWRA J Am Water Resour Assoc* 46(3):447–460.
23. Feeley TJ, III, et al. (2008) Water: A critical resource in the thermoelectric power industry. *Energy* 33(1):1–11.
24. Scown CD, Horvath A, McKone TE (2011) Water footprint of U.S. transportation fuels. *Environ Sci Technol* 45(7):2541–2553.
25. Fulton J, Cooley H (2015) The water footprint of California's energy system, 1990-2012. *Environ Sci Technol* 49(6):3314–3321.
26. Hussey K, Pittock J (2012) The energy–water nexus: Managing the links between energy and water for a sustainable future. *Ecol Soc* 17(1):31.
27. Pittock J (2011) National climate change policies and sustainable water management: Conflicts and synergies. *Ecol Soc* 16(2):25.
28. Scott CA, et al. (2011) Policy and institutional dimensions of the water–energy nexus. *Energy Policy* 39(10):6622–6630.
29. Lenzen M, et al. (2013) International trade of scarce water. *Ecol Econ* 94:78–85.
30. Wiedmann TO, et al. (2013) The material footprint of nations. *Proc Natl Acad Sci USA* 112(20):6271–6276.
31. Barrett J, et al. (2013) Consumption-based GHG emission accounting: A UK case study. *Clim Policy* 13(4):451–470.
32. Peters GP, Hertwich EG (2008) CO_2 embodied in international trade with implications for global climate policy. *Environ Sci Technol* 42(5):1401–1407.
33. Hertwich EG, Peters GP (2009) Carbon footprint of nations: A global, trade-linked analysis. *Environ Sci Technol* 43(16):6414–6420.
34. Peters GP, Minx JC, Weber CL, Edenhofer O (2011) Growth in emission transfers via international trade from 1990 to 2008. *Proc Natl Acad Sci USA* 108(21):8903–8908.
35. Hoekstra AY, Mekonnen MM (2012) The water footprint of humanity. *Proc Natl Acad Sci USA* 109(9):3232–3237.
36. Weinzettel J, Hertwich EG, Peters GP, Steen-Olsen K, Galli A (2013) Affluence drives the global displacement of land use. *Glob Environ Change* 23(2):433–438.
37. Yu Y, Feng K, Hubacek K (2013) Tele-connecting local consumption to global land use. *Glob Environ Change* 23(5):1178–1186.
38. Lenzen M, et al. (2012) International trade drives biodiversity threats in developing nations. *Nature* 486(7401):109–112.
39. Davis SJ, Caldeira K (2010) Consumption-based accounting of CO2 emissions. *Proc Natl Acad Sci USA* 107(12):5687–5692.
40. Steinberger JK, Roberts JT, Peters GP, Baiocchi G (2012) Pathways of human development and carbon emissions embodied in trade. *Nat Clim Chang* 2(2):81–85.
41. Rulli MC, Saviori A, D'Odorico P (2013) Global land and water grabbing. *Proc Natl Acad Sci USA* 110(3):892–897.
42. Daniels PL, Lenzen M, Kenway SJ (2011) The ins and outs of water use—a review of multi-region input–output analysis and water footprints for regional sustainability analysis and policy. *Econ Syst Res* 23(4):353–370.
43. Sovacool BK, Sovacool KE (2009) Identifying future electricity–water tradeoffs in the United States. *Energy Policy* 37(7):2763–2773.
44. Pagiola S, Von Ritter K, Bishop J, Conservancy N (2004) *Assessing the economic value of ecosystem conservation* (World Bank, Environment Department, Washington, DC).
45. Zhang C, Anadon LD (2013) Life cycle water use of energy production and its environmental impacts in China. *Environ Sci Technol* 47(24):14459–14467.
46. Aguiar A, McDougall R, Narayanan B (2012) *Global Trade, Assistance, and Production: The GTAP 8 Data Base* (Center for Global Trade Analysis, Purdue Univ, West Lafayette, IN).
47. Flörke M, et al. (2013) Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. *Glob Environ Change* 23(1):144–156.
48. Vassolo S, Döll P (2005) Global-scale gridded estimates of thermoelectric power and manufacturing water use. *Water Resour Res* 41(4):W04010.
49. Alcamo J, et al. (2003) Development and testing of the WaterGAP 2 global model of water use and availability. *Hydrol Sci* 48(3):317–337.
50. Cullis J, O'Regan D (2004) Targeting the water-poor through water poverty mapping. *Water Policy* 6(5):397–411.
51. Sullivan C (2002) Calculating a Water Poverty Index. *World Dev* 30(7):1195–1210.
52. Ohlsson L (2000) Water conflicts and social resource scarcity. *Phys Chem Earth, Part B Hydrol Oceans Atmos* 25(3):213–220.
53. Pfister S, Koehler A, Hellweg S (2009) Assessing the environmental impacts of freshwater consumption in LCA. *Environ Sci Technol* 43(11):4098–4104.
54. Turner WR, et al. (2012) Global biodiversity conservation and the alleviation of poverty. *Bioscience* 62(1):85–92.
55. Kounina A, et al. (2012) Review of methods addressing freshwater use in life cycle inventory and impact assessment. *Int J Life Cycle Assess* 18(3):707–721.
56. Sullivan C, Meigh J, Lawrence P (2006) Application of the Water Poverty Index at different scales: A cautionary tale. *Water Int* 31(3):412–426.
57. Liu J, Diamond J (2005) China's environment in a globalizing world. *Nature* 435(7046): 1179–1186.
58. Zhang Z, Shi M, Yang H, Chapagain A (2011) An input–output analysis of trends in virtual water trade and the impact on water resources and uses in China. *Econ Syst Res* 23(4):431–446.
59. Yu C (2011) China's water crisis needs more than words. *Nature* 470(7334):307–307.
60. Zhao X, et al. (2015) Physical and virtual water transfers for regional water stress alleviation in China. *Proc Natl Acad Sci USA* 112(4):1031–1035.
61. Feng K, Hubacek K, Pfister S, Yu Y, Sun L (2014) Virtual scarce water in China. *Environ Sci Technol* 48(14):7704–7713.
62. Suh S, et al. (2004) System boundary selection in life-cycle inventories using hybrid approaches. *Environ Sci Technol* 38(3):657–664.
63. Wiedmann T (2009) A review of recent multi-region input–output models used for consumption-based emission and resource accounting. *Ecol Econ* 69(2):211–222.
64. U.S. Department of Energy (2006) *Energy Demands on Water Resources: Report to Congress on the Interdependency of Energy and Water* (U.S. Department of Energy, Washington, D.C.).
65. Li Y, Hewitt CN (2008) The effect of trade between China and the UK on national and global carbon dioxide emissions. *Energy Policy* 36(6):1907–1914.
66. Machado G, Schaeffer R, Worrell E (2001) Energy and carbon embodied in the international trade of Brazil: An input–output approach. *Ecol Econ* 39(3):409–424.

67. Wyckoff AW, Roop JM (1994) The embodiment of carbon in imports of manufactured products: Implications for international agreements on greenhouse gas emissions. *Energy Policy* 22(3):187–194.
68. Lenzen M, Murray J, Sack F, Wiedmann T (2007) Shared producer and consumer responsibility—Theory and practice. *Ecol Econ* 61(1):27–42.
69. Marston L, Konar M, Cai X, Troy TJ (2015) Virtual groundwater transfers from overexploited aquifers in the United States. *Proc Natl Acad Sci USA* 112(28):8561–8566.
70. Wu M, Mintz M, Wang M, Arora S (2009) Water consumption in the production of ethanol and petroleum gasoline. *Environ Manage* 44(5):981–997.
71. Feng K, Chapagain A, Suh S, Pfister S, Hubacek K (2011) Comparison of bottom-up and top-down approaches to calculating the water footprints of nations. *Econ Syst Res* 23(4):371–385.
72. Gleick PH (2003) Global freshwater resources: Soft-path solutions for the 21st century. *Science* 302(5650):1524–1528.
73. Mekonnen MM, Hoekstra AY (2014) Water footprint benchmarks for crop production: A first global assessment. *Ecol Indic* 46:214–223.
74. Spash CL, Aslaksen I (2015) Re-establishing an ecological discourse in the policy debate over how to value ecosystems and biodiversity. *J Environ Manage* 159:245–253.
75. Lo AY, Spash CL (2013) Deliberative monetary valuation: in search of a democratic and value plural approach to environmental policy: Deliberative monetary valuation. *J Econ Surv* 27(4):768–789.
76. Intergovernmental Panel on Climate Change (2013) *Summary for Policymakers. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ Press, Cambridge, UK).
77. Peters GP (2010) Carbon footprints and embodied carbon at multiple scales. *Curr Opin Environ Sustain* 2(4):245–250.
78. McDougall RA, Dimaranan BV (2002) Guide to the GTAP data base. *Glob Trade Assist Prod GTAP* 5:8–1.
79. Peters GP, Andrew R, Lennox J (2011) Constructing an environmentally-extended multiregional input–output table using the GTAP database. *Econ Syst Res* 23(2):131–152.
80. Döll P, Siebert S (2002) Global modeling of irrigation water requirements. *Water Resour Res* 38(4):8–1.
81. Leontief W (1970) Environmental repercussions and the economic structure: An input-output approach. *Rev Econ Stat* 52(3):262–271.

Supplementary Information: Global impacts of energy demand on the water resources of nations

SUPPLEMENTARY METHODS

S1. The GTAP-MRIO table

GTAP (the Global Trade Analysis Project) constructs a database of harmonised country/region input-output tables and trade data between nations on a regular basis (1, 2). The version used in this analysis is constructed from 2007 global economic data containing domestic and international monetary transactions between 57 industry sectors (Table S1) and final consumers (made up of mainly households and government) across 129 countries/regions (Table S2), following the method outlined in (1). Trade data between country/regions is prioritised and input-output tables make the links between the trade sets. This compiles a global database of monetary transactions describing bilateral trade patterns, production, consumption and intermediate use of commodities and services.

S2. The global integrated water model WaterGAP

Since its development the global integrated water model WaterGAP (3, 4) has been used extensively to examine aspects of freshwater use (both consumption and withdrawal) relating to agriculture, industry and domestic sectors both historically and under future scenarios (e.g. ref. 5–9). Below we provide a fully referenced outline of the WaterGAP model (3). We would refer readers to ref. 10 for a detailed description of the WaterGAP hydrological model including calculation of the freshwater fluxes and storages (e.g. canopy, groundwater, snow), its calibration and regionalisation, and brief introduction to the freshwater use models. A comparison of WaterGAP with other land surface and global hydrological models is provided by (11).

As within the main body of the text, throughout the description we distinguish three terms using the definition provided in (12), such that: (i) freshwater *consumption* refers to fresh water withdrawn from a source that is then unavailable within the river basin for other uses; (ii) freshwater *withdrawal* refers to fresh water that is withdrawn from a source and then returned to the river basin although possible in an altered state; (iii) freshwater *use* refers to either consumption or withdrawal and so is used in instance where the WaterGAP model is calculating both measures.

WaterGAP is composed of two main components: (i) a water balance model to simulate the characteristic macro-scale behaviour of the terrestrial water cycle in order to estimate renewable freshwater resources (10) and; (ii) a water use model to estimate freshwater withdrawals and consumption for agriculture (3, 7, 13), electric (8), industry (8), and domestic purposes (5). The model operates on a 0.5 × 0.5 degree grid resolution and river basin scale.

The WaterGAP Hydrology Model has baseline data for 1971 to 2000 from daily meteorological data (precipitation, temperature, radiation) as developed within the EU WATCH programme (15). The hydrological model calculates the daily freshwater balance for each grid cell, taking into account physiographic characteristics like soil type, vegetation, slope, and aquifer type. River discharge is the integral result of runoff generation, freshwater losses by evaporation from surface water bodies, positive or negative net abstractions from surface water bodies and groundwater, and routing processes, taking into account the extent and hydrological influence of lakes, reservoirs, dams, and wetlands. The global drainage direction map DDM30 (16) is used to route the discharge through the stream network until it reaches the ocean or an inland sink. WaterGAP is calibrated against observed mean annual river discharge at 1319 gauging stations globally in a basin-specific manner by varying one soil parameter (and up to two correction factors) (17, 18). In order to compensate for natural inter-annual climate variability, the resultant simulated fluxes are aggregated to long-term annual averages.

Within WaterGAP spatially distributed sectorial freshwater withdrawals and consumption are simulated for the five most important freshwater use sectors: irrigation (3, 7, 13), livestock (3), industry(8), thermal electricity production (8), and domestic (5). Our analysis is based on the values for freshwater consumption for these sectors.

Countrywide estimates of freshwater use in the manufacturing and domestic sectors are calculated based on data from national statistics and reports and are then allocated to grid cells within the country based on the geo-referenced population density and urban population maps (19, 20) as described in (14).

The amount of cooling freshwater consumed and withdrawn (the latter not used in the current analysis) for thermal electricity production is determined by multiplying the annual thermal electricity production with the freshwater use intensity of each power station, respectively. Input data on location, type and size of power stations were based on the World Electric Power Plants Data Set (21). The freshwater use intensity is impacted by the cooling system and the source of fuel of the power station. Four types of fuels (biomass and waste, nuclear, natural gas and oil, coal and petroleum) with three types of cooling systems (tower cooling, once-through cooling, ponds) are distinguished (22).

Irrigation freshwater consumption reflects the optimum supply of freshwater to irrigated plants and is computed based on a global map of irrigated areas (23, 24) and climate conditions. Current climate conditions are represented by the WATCH climate forcing 1971-2000 data (15). The model simulates cropping patterns, growing seasons, and irrigation freshwater withdrawals and consumption distinguishing 18 crop types (7) on a 5 by 5 arc minute spatial resolution. However, these numbers were aggregated to 0.5×0.5 degree raster cells to fit the resolution of the hydrological model (and other freshwater use models). Country specific irrigation freshwater withdrawals and consumption are calculated by taking into account national irrigation project efficiencies, which reflect the state of irrigation technology within each country. These efficiency factors consider conveyance losses, field sizes and management practices. A detailed discussion of irrigation in global hydrological models including WaterGAP is provided by (25).

Freshwater use for livestock are computed by multiplying the number of animals per grid cell by the livestock-specific freshwater use intensity (3) with values of freshwater consumption and withdrawal assumed to be the same.

To provide context for the analysis we provide a breakdown of proportional freshwater consumption represented in the WaterGAP hydrological model by aggregated economic sectors (Table S3) and regions (Table S4) following the categories in Tables S1 and S2 respectively. This represent the underlying hydrological data before freshwater consumption is reattributed to final demand using the EE-MRIO model (see next section). We refer readers to the corresponding reference that describe detailed spatial patterns for agricultural (13), electric (8), industrial (8), and domestic use (5).

S3. Integration of the WaterGAP and MRIO models

Integration of the WaterGAP and MRIO model into an environmentally extended multi-region input output model (EE-MRIO) was achieved by crosslinking geographic and sectorial data from each of the models described above. Geographically, national scale data on freshwater consumption from the WaterGAP model were linked to the corresponding country/region in the GTAP model using the spatial join function in the geographical information system ArcGIS 10.1 (ESRI, Redlands, California).

From this geographically linked data, GTAP country/region specific values for freshwater consumption for each of the 57 sectors were calculated based on three different strategies, depending on the level of data aggregation in the WaterGAP and GTAP models;

1. For each of the 129 GTAP countries/regions, freshwater consumption data for 19 crop and 12 livestock sectors (3, 7, 13) associated with WaterGAP was aggregated into the eight crop and two livestock sectors represented in GTAP using the cross mapping detailed in Table S5. In this instance there was a direct link between WaterGAP and GTAP categories that simply required aggregation of WaterGAP data.
2. Values for Electricity and Domestic freshwater consumption taken directly from WaterGAP (5, 8) were allocated to the corresponding country/region and the Electricity and Dwellings sectors in GTAP. As with step 1 (above) we create a direct link between freshwater consumption in WaterGAP and corresponding GTAP sectors.
3. WaterGAP allocates all other industry freshwater consumption (8) into one aggregated Industry sector that accounts for 5.61% of total freshwater consumption (Table S3). To create the link between WaterGAP and GTAP, country/region specific values from the WaterGAP industry sector are apportioned to the remaining GTAP sectors based on the expenditure of each sector on the GTAP water sector. Here the strength of the economic interaction with the GTAP water sector is taken as indicative of differences in freshwater consumption between the GTAP

sectors. For example if 90% of the interaction between the GTAP water sector and the remaining GTAP sectors not assigned a value in steps 1 and 2 related to Petroleum, 90% of the industrial freshwater consumption in the WaterGAP model would be assigned to the Petroleum sector, with the remainder shared in proportion to the strength of interaction among the other GTAP sectors and the GTAP water sector.

Freshwater consumption by sector is used as the environmental extension to the MRIO model, and MRIO analysis reallocates direct industry freshwater consumption to the country/region of final consumption via the product in which it becomes embodied. Freshwater consumed directly by households (i.e. from their taps) is not an intermediate industry and therefore is directly allocated to dwellings post-analysis.

As detailed in the Data Description section, the WaterGAP model uses climate data from 1971-2000 in order to compensate for natural inter-annual climate variability, with the resultant simulated fluxes aggregated to long-term annual averages and so are considered to represent current conditions. Freshwater consumption associated with irrigation is calculated from this average based on a global map of irrigated areas (26), with all other sectors (i.e. industry, domestic, electricity) modelled to reflect 2005 values based on key socio-economic drivers varying between countries (14). The GTAP 8 database provides information on trade flows for 2007. In using these data sources we attempted to match time periods as closely as possible. The analysis will therefore not capture the influence of unusual weather conditions, for example periods of extended drought in Australia and the USA. Similarly, the energy sectors will not capture significant changes in energy policy that may have happened post 2007. This is most relevant in relation to unconventional (shale) gas in the USA.

S3.1. EE-MRIO analysis

In the environmentally extended input-output analysis presented here, freshwater directly consumed by GTAP sectors is reallocated through complex supply chains to the finished products in which it becomes ‘embodied’ using the standard input-output equation originating from Leontief (27), and used by many in footprint analysis. Within our EE-MRIO model, total freshwater consumption for a focal country/region is the sum of embodied freshwater for that country/region resulting from absolute demand for finished products from all 57 GTAP sectors. For an individual GTAP sector (e.g. petroleum) within the focal country/region, freshwater consumption embodied in the final product provided by this sector can be traced back to the sectors and countries/regions in which freshwater was originally consumed using standard input-output techniques.

Formally, environmentally extended input-output analysis enables calculation of freshwater consumption required to satisfy final demand for a product using the equation $\boldsymbol{F} = \boldsymbol{f_x}\mathrm{Ly}$. Here $\boldsymbol{F}$ is total freshwater consumption, $\boldsymbol{f_x}$ is a measure of industrial freshwater intensity (m^3 yr^{-1} per $ sectorial output), y is the specific demand, and L is the Leontif inverse $(\boldsymbol{I}-\boldsymbol{T}\widehat{\boldsymbol{x}})^{-\mathbf{1}}$ of the multi-region input output table $\boldsymbol{T}$ that describes the global supply chain network. Multiplying the sectorial production requirements globally **L,** by the direct freshwater intensity of each sector $\mathbf{F_x}$ for the specified demand **y** calculates total freshwater consumption **F**. The spatial distribution of freshwater consumption can be calculated globally $\mathbf{F_{total}}$, for a regions demand such as the USA $\mathbf{F_{USA}}$, or demand for a specific commodity such as petroleum $\mathbf{F_P}$. From this equation it can be calculated that, for example, demand for petroleum $\mathbf{y_p}$ not only consumes freshwater within the petroleum sector itself (direct freshwater consumption) but also drives consumption of freshwater associated with other sectors worldwide (indirect freshwater consumption) required as inputs upstream in the production of petroleum, representing the global supply chain network described by the multi-region input-output table **T**.

S3.2. Induced economic activity and associated freshwater consumption

The induced global economic activity and associated freshwater consumption from producing an additional unit ($1) of USA petroleum was calculated using the equation $\boldsymbol{F}=\boldsymbol{f_x}\,'\boldsymbol{L_{USA-P}}$. Each column in L represents the additional (economic) units of production required by each sector in each country/region to produce an additional unit of output. The vector global freshwater intensity is transposed and multiplied by the column in $\boldsymbol{L}$ representing the USA petroleum sector.

S3.3 Validation of freshwater consumption within the MRIO.

To validate the approach to assembling our EE-MRIO we compared figures for freshwater consumption across energy sectors in our model to values provided in previous published studies. Freshwater consumption associated with electric generation has been extensively discussed and validated (8) so we limit our assessment to the GTAP coal, oil and gas sectors (representing the extractive phase) and petroleum and gas manufacturing and distribution sectors (see Table S1).

Within the literature, as noted in (28), while a large number of studies state figures for freshwater consumption, most of these are derived from a few individual studies. Of these, figures provided in the review of (29) are commonly employed to calculate total freshwater consumption for energy systems. To examine our data within the context of other published figures we assembled independent values for freshwater consumption across the five energy sectors from data provided in (28–33). To allow comparison between studies that consider freshwater consumption at a range of different scales from individual plants to geographic regions, we standardised values from the literature to freshwater consumption per unit energy (m^3 per terajoule). We calculate a global average figure (m^3 per terajoule) for each of the energy sectors within our EE-MRIO allowing comparisons with other studies that use such a figure (see Section S5).

Results from this analysis (Fig. S2) demonstrate that in all cases our global estimates of freshwater consumption per unit energy fall within the range of previous studies. For coal and gas extraction and refining/distribution our calculated figures fall close to the median values for freshwater consumption. Our estimates for oil extraction and the petroleum sector fall within the lower quartile, although these sectors have a large spread of values within the literature. These results suggest that the figures that we have arrived at independently for freshwater consumption based on links between the WaterGAP hydrological model and trade flows represented in the MRIO have provided robust estimates of freshwater consumption.

S4. Mapping freshwater consumption to high resolution

Country/regional patterns of freshwater consumption were mapped to 0.5 x 0.5 degree grid cells using a modification the approach of (34) who examined spatial heterogeneity in freshwater consumption for agriculture and industry, and (8) who investigated spatial patterns of freshwater use for power generation.

In the first instance country/region totals for freshwater consumption in each sector were derived from the EE-MRIO and apportioned back to the country/region and sector which extracted the freshwater, now with the knowledge of the product consumption that drove this extraction. These country/region totals from the EE-MRIO were then assigned to each 0.5 × 0.5 degree grid cell in proportion to intensity of freshwater consumption for the corresponding sector within that 0.5 × 0.5 degree grid cell derived from WaterGAP. Due to data availability a number of different approaches were taken to allocate freshwater consumption to each 0.5 × 0.5 degree grid cell;

1. For crops and livestock described in Table S5, data at a 0.5 × 0.5 degree grid cell resolution describing freshwater consumption was available from the WaterGAP model (3, 13). This spatial data was aggregated to sectors as described in Table S5 to produce 0.5 × 0.5 degree grid cell resolution data of freshwater consumption within each country/region corresponding to crop and livestock sectors within the EE-MRIO. Regional/country totals for freshwater consumption calculated from the EE-MRIO were apportioned among 0.5 × 0.5 degree grid cells based on the intensity of consumption for the corresponding sectors as described by the 0.5 × 0.5 degree grid cell resolution WaterGAP model. Patterns of freshwater consumption are therefore representative of intensity of activity within the country/region for the corresponding sector within each 0.5 × 0.5 degree grid cell.
2. Regional/country scale freshwater consumption totals for Dwelling and Electricity calculated from the EE-MRIO model were mapped to a high resolution using the corresponding Dwelling and Electricity data from WaterGAP (5, 8). Again this mapping was performed in relation to intensity of freshwater consumption in the high resolution spatial WaterGAP dataset.
3. For the coal sector, minerals sector, mineral products NEC and ferrous metals sectors within the EE-MRIO (see Table S1) data on areas of production were obtained from the United States

Geological Survey's Mineral Resources Program. Point data from this source were assigned to each of the 0.5 × 0.5 degree grid cells used by the WaterGAP model. Either totals for production (when available) or total number of facilities were used to produce a weighting for each grid cell that reflect intensity of activity. Total freshwater consumption at the country/region scale for the corresponding GTAP sector calculated from the EE-MRIO was then mapped to the 0.5 × 0.5 degree grid cell resolution using this weighting to reflect intensity of freshwater consumption.

4. Spatial data relating to the location of facilities of relevance for the oil sector, gas sector, and petroleum sector within the EE-MRIO were obtained from the IHS International Exploration & Production Database (35). This represents one of the most complete datasets on the location of exploration and production activity associated with these sectors that is available. Due to incomplete data on extraction and production rates for some facilities we used total number of facilities per 0.5 × 0.5 degree grid cell as an indicator of the intensity of these sectors to generate a weighting. Total freshwater consumption at the country/region scale calculated in the EE-MRIO for the corresponding GTAP sector was apportioned to each 0.5 × 0.5 degree grid cell based on this weighting of activity. This approach is comparable to the established method used by (8) to map freshwater use associated with power plants. Ref. 8 used atlas data of the location of power plants globally to spatially locate the activity within each 0.5 × 0.5 degree grid cell used in the WaterGAP model. Combined with production values for each power plant and industry standard figures for freshwater withdrawal and consumption, this spatial data was used to calculate total freshwater use within each 0.5 × 0.5 degree grid cell. In our analysis data from the IHS International Exploration & Production Database (35) provides the point localities of activity associated with the oil, gas, and petroleum sectors allowing us to spatially locate activity within each 0.5 × 0.5 degree grid cell. Using the method described in Section S3 we have independently calculated country/regional figures for freshwater consumption associated with these sectors and validated this against figures from the literature for freshwater consumption associated with energy production for the corresponding sectors (Fig. S2; Section S3.3). Unlike (8), data on production capacity of facilities is not consistently available in the IHS dataset so we have assumed that the number of plants within a 0.5 × 0.5 degree grid cell is indicative of demand for freshwater resources and apportioned country/regional totals of freshwater consumption correspondingly. For example where a country/region to have two grid cells one containing a single facility and the other nine facilities we would assign 90% of the country/regions sectors associated freshwater consumption derived from the EE-MRIO to the latter 0.5 × 0.5 degree grid cell.
5. For the remaining sectors in the WaterGAP-MRIO model, freshwater consumption not already accounted for in steps 1-4 within the industrial sector of WaterGAP was used as the measure of intensity of freshwater consumption within each 0.5 × 0.5 degree grid cell. Country/regional

totals of freshwater consumption calculated in the EE-MRIO for these remaining sectors were apportioned among grid cells in relation to intensity of fresh consumption as indicated in WaterGAP (5, 8), after accounting for that already assigned in the previous steps.

This approach has two implications. Firstly, 95% of global freshwater consumption represented in the WaterGAP model is associated with sectors considered in steps 1 and 2. Here the direct link between the sectors within the EE-MRIO and the 0.5 × 0.5 degree grid cell freshwater consumption data provided by the WaterGAP model suggests that mapping of spatial pattern of freshwater consumption for these sectors will be realistic: (i) given the limits of the WaterGAP model (see previous description and reference within); (ii) acknowledging that patterns reflect intensity of freshwater consumption per 0.5 × 0.5 degree grid cell and so do not trace individual supply chains (see discussion in main text and below). In steps 3 and 4 we have attempted to spatially locate critical pathways for the EE-MRIO using spatial data from a range of sources. This adds uncertainty in relation to the underlying dataset in terms of completeness of data captured and differences in intensity of production. Finally, the least accurate part of the spatial mapping relates to step 5 which aggregates a number of industrial GTAP sectors. Mapping to each 0.5 × 0.5 degree grid cell is based on this aggregate value and so reflects general patterns of freshwater consumption associated with industry and not specific sectors within the EE-MRIO. As a result of these limitations, highest confidence in spatial patterns of freshwater consumption at 0.5 × 0.5 degree grid cell resolution should be placed on energy sectors that induce a higher proportion of freshwater consumption associated sectors within steps 1 and 2. With reference to Fig. 2 (main text) data mapped in steps 1 and 2 accounts for between 87% and 99% of freshwater consumption for the USA, and between 55% and 84% for China. For the USA, freshwater consumption mapped using step 3-4 accounts for between 1% and 5% of the total, rising to between 5% and 28% for China. For these sectors patterns of freshwater consumption will reflect areas of production however, absolute amounts may vary between 0.5 × 0.5 degree grid cells due to different production rates or water use efficiencies of industrial processes. Across both countries step 5 accounts for between 3% and 17% of total freshwater consumption depending on sector (see Fig. 2). Here patterns of freshwater consumption per 0.5 × 0.5 degree grid cell associated with the energy sectors reflect overall patterns of freshwater consumption associated with industrial activity and so lack sector specificity.

The second implication of this approach relates to specific supply chains. In mapping to a high resolution we have assumed that country/region freshwater consumption for a specific sector within the EE-MRIO occurs in relation to the intensity of freshwater consumption within the 0.5 × 0.5 degree grid resolution of the WaterGAP model. As such, for any given sector, freshwater consumption will occur across all 0.5 × 0.5 degree grid cells in which it is modelled to occur within WaterGAP, with the contribution weighted by intensity of freshwater consumption. In reality there will be specific supply chains associated with international trade such that demand for a specific product could be traced to a specific location. This level of detail requires a bottom-up approach where data on individual processes are collected (see Section 5). While bottom-up approaches can provide the level of detail to resolve such differences, for example, among different alloys of steel sourced from different countries, a product such as petroleum production can require thousands of inputs each developed in a separate process which in turn require inputs from other processes and so on. Identifying each input among a complex web of supply chains is impossible, and limits analysis to the major inputs at each stage leading to truncation error. Hybrid models have been developed to balance the detail of bottom-up life-cycle methods with the global coverage of top-down methods (36–38). For example (39) integrate a process database representing the major inputs of energy technologies with a two-region multi-region input-output model to complete the product system and determine those process that occur domestically and internationally. Understanding this limitation means that policy makers could invest resources in tracing critical pathways to understand specific supply chains in more detail. In our analysis this limitation manifests itself in terms of strong correlations between patterns of freshwater consumption (Section S4.1; Table S6) between sectors and countries/region which reflects common areas of human economic activity. Differences express themselves in terms of absolute amounts of freshwater consumption (Table S6).

S4.1 Comparison of spatial patterns of energy sectors

For each of the energy sectors correlation coefficients were calculated to compare patterns in the spatial distribution of freshwater consumption between the USA and China. Due to non-normality of the data they were first transformed to rank order. To account for spatial autocorrelation, correlations were then calculated and their significance assessed using a modified *t* test that adjusts the degrees of freedom based on an estimate of the effective sample size (40). Calculation were performed using the SpatialPack (41) in R (42) (see Table S6). Differences in absolute amounts of freshwater consumption between countries were then calculated based on the Wilcoxon signed-rank test. Results are presented in Table S6 and demonstrate strong positive correlation between measures driven by common areas of both freshwater consumption associated with human activity, and areas of low freshwater consumption where there is little human economic activity. Wilcoxon signed-rank test indicate significant differences between absolute consumption patterns between the USA and China reflecting the differing patterns of territorial and international consumption (Fig. 2).

S5 Our contribution to water footprinting developments

To our knowledge, our analysis is the first top-down global grid-based freshwater footprint assessment of the water-energy nexus. Results allow for an improved assessment of freshwater impacts of energy demand at sub-national geographic scales. This is critically important given the uneven distribution of both freshwater resources and adaptive capacity to deal with pressure placed on them. Freshwater consumption data from the WaterGap model is attributed to demand for product groups in the MRIO analysis, however, instead of ending our analysis here as has been done previously, we map freshwater consumption by the final consumption activity revealing spatial patterns in demand globally. In other words, the first stage of our analysis (Section S3) tells us the product group in which freshwater is embodied, but does not refine the geographical location beyond country/regional scale of different supply chain components which could be produced under differing conditions of freshwater scarcity. The second part of our analysis (Section S4) provides this spatial information by using known location of human activities from the WaterGAP model to understand geographic patterns of freshwater consumption which can then be considered in the context of freshwater scarcity (Section S6). The method we employ is not just applicable to freshwater embodied in energy consumption, but can be applied to freshwater consumption (and withdrawal) driven by demand for any product group.

We provide a brief overview of methodological approaches to examining freshwater consumption associated with human activity in the following section. This is not intended to be a comprehensive review, for which we would direct readers to (43–45), rather we highlight differences in approaches allowing readers to understand the contribution of our study to this field and its context within the wider literature.

S5.1 Context of previous freshwater footprinting studies

A wide spectrum of methodological approaches have been developed for freshwater footprinting leading to discrepancies between model outcomes. Studies employ different bottom-up and top-down methodologies (43, 46); different freshwater "colours" (e.g. green, blue and grey) (34, 47); at different spatial scales of analysis from within countries (48, 49) to international trade flows (34, 50); some are purely inventory-based (51) whereas others measure localised impacts in terms of freshwater stress (49) and implications for human health and ecosystem deterioration (44, 49, 52–54); and studies attribute freshwater use to different intermediate and final consumers (43, 46).

The majority of freshwater footprinting studies have used bottom-up data and focused on agriculture related products, being the dominant source of freshwater consumption (43, 45, 46, 55). These studies tend to be aligned with the high spatial resolution of hydrological models, at 50 × 50 km grid cell resolution (52, 56). Spatially explicit freshwater footprints exist for food products and the final demand of individual countries, with a few bottom-up studies extending their inventory to include an impact assessment on freshwater stress, human health and ecosystem deterioration (44, 49, 52–54). These studies observe that freshwater stress has a range of consequences for society including reduced hygiene, spread of disease, reduced water availability for irrigation and malnutrition (see Section S6).

Bottom-up approaches provide a measure of operational freshwater consumption of main supply chain components, and hence neglect embodied fresh water upstream of this. For example the indirect fresh water required for energy used to manufacture the components of power stations and machinery; the fresh water used to manufacture the modes of transport for energy distribution; and so forth. From this perspective they generally give lower estimates than top-down approaches covering the full supply chain (46). Bottom-up analyses attribute freshwater consumption to the country in which the final product is consumed by multiplying freshwater production intensities with bilateral trade statistics, as is the approach taken by the Water Footprint Network (47). Such an approach does not determine whether the product is used by an intermediate (industry) or final (household) consumer (46), and hence assigns higher estimates to export-rich countries compared to top-down studies which can track exported products which are reimported to countries.

In comparison to the bottom-up approach, a number of studies have employed top-down multi-regional analysis (as used in the current study) to calculate total embodied fresh water of all products traded in an economy (i.e. not restricted to operational fresh water use) (30, 50, 57, 58). Goods and services are aggregated into economic product sectors, and sales and purchases between sectors and across countries are recorded. Detailed physical data on freshwater use (consumption or withdrawal) by crops and livestock are summed directly to economic agriculture sectors. However national electricity and industry freshwater consumption reported by hydrological models are usually given as one value and need to be disaggregated to corresponding economic industrial sectors (e.g. mining, manufacturing, transport, commercial and public services) based on their relative purchases from the freshwater production and distribution sector (59) or industrial turnover (50). Sectorial estimates for non-agricultural products tend to be higher compared to bottom-up approaches as they take into account when agricultural products are used as supply chain inputs (46). This is particularly true for economies like China that export a lot of manufactured goods. While top-down approaches use national sectorial average values for freshwater productivity instead of explicit cell-based productivities (60), they include embodied freshwater content of all supply chain inputs up to the point of final consumption. Assessments with more than one country have so far reported results at the national level (50, 59, 61), with individual country assessments reporting data at the watershed or administrative unit scale (58, 62).

In top-down approaches aggregated sectorial groupings (e.g. chemical production; electronic equipment) have been disaggregated by proportionally assigning production activities to economic output (63). Such disaggregation assumes the two products are produced using the same resource inputs with the same pollution intensity, but in proportion to their annual turnover. For carbon this could be deemed appropriate due to its impact not being felt directly at the point of production, but for freshwater resources it is less adequate as the impact would just be averaged out in proportion to economic output, not the specific location of freshwater intensive industries. Hence it does not address actual pressure on freshwater resources (45). The input mix can be manually adjusted to better represent physical characteristics of individual products (64). Such attempts are intended to yield a compromise between data accuracy and data availability (63).

In the current study we have extended the national scope of the EE-MRIO results to attribute supply chain freshwater requirements to 0.5 × 0.5 degree grid cells based on both the physical location and intensity of production activities. Due to data limitations in our analysis this has been performed specifically for crops and livestock production; power plants; and energy and mineral production (SI sections 1-3); this has yet to be fully achieved in another study. The remaining few percent of freshwater consumption whose grid cell location is unknown is assigned proportionally across countries/regions weighted by freshwater intensity of activity in each 0.5 × 0.5 degree grid cell for the corresponding sector. Wenz et al. (63) advocate such advances where the use of non-input-output data can improve the approximation of a certain input or output flow. This extension goes some way to addressing the well documented problems of sectorial and regional aggregation in input-output models (63), as external data sources are used to assign freshwater consumption to specific areas in proportion to patterns of sector specific industrial concentration.

S6. Implications of freshwater consumption.

First order scarcity

Freshwater consumption associated with the petroleum, electric and gas sectors for the USA and China was examined in the context of first order water scarcity using a number of metrics. Placing it within the context of first order scarcity is important as activities associated with energy production rarely occur within isolation of other human activities. Freshwater consumption induced by the energy sector will often form part of a complex array of pressures placed upon freshwater resources, reflecting areas of high human economic activity. As such absolute amounts (m^3 yr^{-1}) of freshwater consumption induced by the energy sector considered in the present study are highest in certain areas of China, USA, the Middle East, India and Pakistan (see Fig S3). However, in these regions energy induced freshwater consumption may contribute a comparatively small amount to total freshwater consumption reflecting freshwater intensities of economic sectors (Table S3). A critical question is therefore whether energy induced activity is occurring within a context of overall freshwater scarcity as this has implications for both water and energy security, and associated environmental, social and economic consequences. Thus in this section we employ two indices that consider physical freshwater availability to provide this context.

In our assessment of first order scarcity in each case the total renewable freshwater resource per river basin was calculated from the WaterGAP model (10). Data on freshwater consumption for the three energy sectors were aggregated to represent total freshwater consumption for the USA and China.

Adapted Falkenmark water stress indicator.

The Falkenmark water stress indicator (65) is one of the most widely employed measures used to examine freshwater scarcity (53) and is based on the relationship between freshwater availability and human population. Population data for 2005 at a 0.5 × 0.5 degree grid resolution were obtained from (66) and aggregated to total population per river basin as defined in WaterGAP. The basin specific Falkenmark water stress indicator was then calculated as the volume of renewable freshwater resources (10) available per person (m^3 yr^{-1} per person). Thresholds for freshwater scarcity were taken from (53) such that (i) river basins with less than 1700 m^3 yr^{-1} per person are considered to experience water stress; (ii) river basins with less than 1000 m^3 yr^{-1} per person are considered to experience water scarcity; and (iii) river basins with less than 500 m^3 yr^{-1} per person are considered to experience absolute scarcity.

Adapted water resources vulnerability index.

The second indicator is based on supply–demand analysis, and considers total annual freshwater withdrawals as a percentage of renewable freshwater resources (53). The WaterGAP model was used to calculate total freshwater withdrawal (as distinct from consumption which has been used as the basis for all previous calculations) for all human activity in each river basin. The ratio of this freshwater withdrawal to renewable freshwater resources (10), expressed as a per cent, represent the water resources vulnerability index for each river basin. Again using thresholds taken from (10) a river basin can be considered as; (i) water scarce if the percentage ratio of withdrawals to availability is between 20% and 40%; and (ii) severely water scarce if the percentage ratio of withdrawals to availability exceeds 40%.

Relationship between freshwater consumption associated with energy and water scarcity.

Bivariate mapping (67) was used to examine the relationship between measure of freshwater scarcity and freshwater consumption associated with the energy sectors of the USA (Fig. S5-S6) and China (Fig. S7-S8). For each analysis we present data on the water scarcity index (panel A and B in Fig. S5-S8) and freshwater consumption associated with energy sectors (panel C and D in Fig. S5-S8) to clarify the relationship revealed by bivariate mapping. Within the bivariate mapping (Panel E and F in Fig. S5-S8) river basins that are indicated by colours in the red and purple spectrum represent those basins where high energy induced freshwater consumption is occurring within a context of high first order water scarcity.

Visually comparing the results of the bivariate maps (Panel F in Fig. S5-S8), fewer river basins with coincident high energy induced freshwater consumption and freshwater scarcity were identified using the Falkenmark water stress indicator (USA Fig. S5 panel F; China Fig. S7 panel F) compared to the water resources vulnerability index (USA Fig. S6 panel F; China Fig. S8 panel F). To identify basins where there was agreement between the measures, commonalities in the bivariate mapping patterns were identified by calculating a coincident index based on overlap between energy induced freshwater consumption and water scarcity (as defined using the two indices described above). Firstly, each basin was assigned to a stress category from low (one) to high (five) based on proposed thresholds for the water scarcity indices (Panel A in Fig. S5-S8; Fig. S9; see description of indicators above). Secondly, total energy induced freshwater consumption in each basin was assigned to a category from low (one) to high (five) based on the logarithmic scale used in the bivariate mapping (Panel C in Fig. S5-S8; Fig. S9). Thirdly, these values were combined to produce a coincident index (Fig. S9) such that areas with high water scarcity and high energy induced freshwater consumption score 10, and correspond to river basins that are indicated by colours in the red and purple spectrum in the bivariate maps (Panel F in Fig. S5-S8). Finally, an ensemble basin score for this coincident index was calculated by taking the average score based on each of the two first order water scarcity indices. As discussed in the main text this ensemble measure of first order scarcity (Fig. 4) identifies a number of major river basins in India, Pakistan, China and the USA as being areas where energy induced freshwater consumption is occurring within a context of significant pressure on renewable freshwater resources.

Second order water scarcity

As technological investment provides mechanisms to adapt to loss of ecosystem function in more affluent regions of the world (68), pressures on freshwater resources are of particular concern where they occur in areas that contains the poorest sectors of society. There are two reasons for this. Firstly, the poor are generally considered to be most directly dependent on ecosystems and the goods and services they provide as they disproportionately earn their living by using their labour to extract value from natural resources (69). Secondly, poor people are particularly vulnerable to physical water scarcity as they lack the social adaptive capacity to deal with such shortages, and the means to obtain those resources from elsewhere (70). For example, farmers in the developed world have higher ‘social adaptive capacity’ to compensate for reductions in freshwater availability through technological fixes, such as drought-tolerant cultivars or drip irrigation, than their poorer Southern counterparts.

Such considerations have been the primary motivation behind attempts to calculate indices of second order water scarcity based on environmental, social and economic aspects of relevance (53). Example of such measures include the Water Poverty Index (71), Water Vulnerability Index (72) and the Social Resource Water Stress/Scarcity index (73) that take a multidimensional approach to assessing second order water scarcity. In such indices data on the available freshwater resources is considered in the context of factors such as access (e.g. improved freshwater supply), the capacity for management of the resource (e.g. institutions, human health), the fresh water used for human activity (e.g. demand for agriculture, industry) and the environmental integrity (71). As discussed by (74), although such indices can be employed at a range of scales they are most useful for localised studies to provide insight for policy and investment. Application at large spatial scales can hide significant variation within areas.

Even at the comparatively course scale of the current analysis (0.5 × 0.5 degree grid cells; river basins) many of the suggested indicators are either not available globally or are aggregated to national measures (e.g. percentage population with access to improved water supply from the Millennium Development Indicators) limiting our ability to perform such a multidimensional analysis of the factors that contribute to second order water scarcity. As a result of these limitations in data availability we performed our analysis at two spatial scales and examined agreement between the different indices.

The Human Development Index (HDI) is a multidimensional measure that captures a range of social, economic and health measures that could influence second order water scarcity (73), however data is only available at national scales. The other measure employed in the current study, percentage of children underweight, captures spatial heterogeneity within countries/regions as it represent values at a 0.5 x 0.5 degree grid resolution. However, this measure captures only a single factor that has been suggested to be an indicator of social adaptive capacity (75). To assess how representative this sub-national measure may be of more complex indices that combine social, economic and health factors (i.e. HDI) we correlated average values for the HDI for 2008 (76) against average percentage of children underweight (77) (see next paragraph for full description) across 127 GTAP geographic countries/regions. The correlation ($r= -0.75$, $df= 118$, $p <0.001$) indicates a strong relationship between increasing values for the HDI and decreasing percentage of children that are underweight. This suggests that the sub-national scale index can provide a useful indicator with which to consider social adaptive capacity.

Furthermore, it is well established that prevalence of child malnutrition is a good proxy for social adaptive capacity and is used in a study with a similar global scope (75). Allied measures of human health (i.e. under -5 child mortality, life expectancy, incidence of disease) are suggested (71, 74) as being a relevant measure for assessment of capacity to manage freshwater resources within assessments of second order water scarcity. For our measure, data from (77) on sub-national prevalence of child malnutrition, calculated as "percentage of children with weight-for-age z-scores more than two standard deviations below the NCHS/CDC/WHO International Reference Population" (77), at a 0.25 × 0.25 degree grid resolution were obtained and aggregated to the 0.5 × 0.5 degree grid used in the current analysis. For a number of sub-national units and countries data was not available. Following the approach of (75), for sub-national units we assigned values equal to the mean value of the percentage of underweight children in the rest of the country. For countries with no data we employed the established approach of (78) and performed a linear regression of country level mean proportion of underweight children against per capita calorific intake values (79). Estimated values from our regression model (adj-r = 0.43, $F = 78.85$, $df = 1,101$, $p<0.01$) for countries with no data available were compared to values for percentage of children aged 0–59 months below minus two standard deviations from median weight-for-age of the World Health Organization (WHO) Child Growth Standards provided in the UNICEF, World Bank and WHO Joint Malnutrition dataset (80). The strong positive correlation between this dataset and our modelled results for countries with no data ($r = 0.77$, $df = 13$, $p < 0.001$) suggests that our estimates are robust.

As with the assessment of first order scarcity, bivariate mapping (67) was used to identify areas of coincident low social adaptive capacity and high energy induced freshwater consumption associated with the USA and China. The calculation was firstly based on values of the HDI at country/region scale (Fig. S10 and S11; USA and China respectively) and then based on prevalence of child malnutrition at 0.5×0.5 degree grid resolution (Fig. S12 and S13; USA and China respectively).

For analysis based on the HDI, as stated in the main text, we find no correlation between freshwater consumption associated with the energy sector for the USA (rho = -0.01, df 119, $P > 0.05$) or China (rho = 0.03, df 119, $P > 0.05$) globally. Using the United Nations Development Programme categorisation of values of the HDI, very high human development is indicated by values above 0.80, high human development 0.70-0.80, medium human development 0.55-0.70, low human development 0-0.55. For consistency with other bivariate maps we split this low category into low 0.40-0.55 and very low < 0.40. Bivariate mapping of HDI using these divisions suggests spatial overlap between countries/regions where high energy induced freshwater consumption is occurring within the context of low and medium values for the HDI (Fig. S10 and S11) in India, Pakistan, China, north-east Africa and parts of the middle-east.

Based on data for prevalence of child malnutrition at 0.5×0.5 degree grid resolution bivariate mapping further refines our understanding of these patterns by highlighting regions of Indian, Pakistan, and sub-Saharan Africa as areas where high energy induced freshwater consumption is occurring in the context of low social adaptive capacity. This agrees with the results of national scale analysis using the HDI, but provides further geographic focus for follow on work. Comparison of patterns in the spatial overlap of energy induced freshwater consumption and both first order scarcity (Fig. 4; Fig. S5-S8 panel F) and social adaptive capacity (Fig. S10-S13) identifies river basins in India and Pakistan as being of particular interest as these represent the overlap between physical scarcity and lack of social adaptive capacity to ameliorate impacts. Future work is required to explore in detail issues of freshwater scarcity in these regions, with particular emphasis on the role of international trade in driving pressures on freshwater resources, the implications of this for fresh water and energy security and the associated social, health and economic consequences.

Supplementary Reference

1. Peters GP, Andrew R, Lennox J (2011) Constructing an environmentally-extended multi-regional input–output table using the GTAP database. *Econ Syst Res* 23(2):131–152.

2. Aguiar A, McDougall R, Narayanan B (2012) Global Trade, Assistance, and Production: The GTAP 8 Data Base. *Cent Glob Trade Anal Purdue Univ*.

3. Alcamo J, et al. (2003) Development and testing of the WaterGAP 2 global model of water use and availability. *Hydrol Sci* 48(3):317–337.

4. Döll P, et al. (2001) The global integrated water model WaterGAP 2.1. *Kassel World Water Ser* 5. Available at: http://www.usf.uni-kassel.de/usf/archiv/dokumente/kwws/5/ew_2_watergap.pdf [Accessed March 3, 2015].

5. Flörke M, et al. (2013) Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. *Glob Environ Change* 23(1):144–156.

6. Pfister S, Bayer P, Koehler A, Hellweg S (2011) Projected water consumption in future global agriculture: Scenarios and related impacts. *Sci Total Environ* 409(20):4206–4216.

7. Beek T aus, et al. (2010) Modelling historical and current irrigation water demand on the continental scale: Europe. *Adv Geosci* 27(27): 79-85.

8. Vassolo S, Döll P (2005) Global-scale gridded estimates of thermoelectric power and manufacturing water use. *Water Resour Res* 41(4):W04010.

9. Haddeland I, et al. (2014) Global water resources affected by human interventions and climate change. *Proc Natl Acad Sci* 111(9):3251–3256.

10. Müller Schmied H, et al. (2014) Sensitivity of simulated global-scale freshwater fluxes and storages to input data, hydrological model structure, human water use and calibration. *Hydrol Earth Syst Sci* 18(9):3511–3538.

11. Haddeland I, et al. (2011) Multimodel Estimate of the Global Terrestrial Water Balance: Setup and First Results. *J Hydrometeorol* 12(5):869–884.

12. Gleick PH (2003) Water Use. *Annu Rev Environ Resour* 28(1):275–314.

13. Döll P, Siebert S (2002) Global modeling of irrigation water requirements. *Water Resour Res* 38(4):8–1.

14. Flörke M, et al. (2013) Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. *Glob Environ Change* 23(1):144–156.

15. Weedon GP, et al. (2011) Creation of the WATCH Forcing Data and Its Use to Assess Global and Regional Reference Crop Evaporation over Land during the Twentieth Century. *J Hydrometeorol* 12(5).

16. Döll P, Lehner B (2002) Validation of a new global 30-min drainage direction map. *J Hydrol* 258(1–4):214–231.

17. Hunger M, Döll P (2008) Value of river discharge data for global-scale hydrological modeling. *Hydrol Earth Syst Sci Discuss* 12(3):841–861.

18. Döll P, Kaspar F, Lehner B (2003) A global hydrological model for deriving water availability indicators: model tuning and validation. *J Hydrol* 270(1–2):105–134.

19. Goldewijk KK (2005) Three Centuries of Global Population Growth: A Spatial Referenced Population (Density) Database for 1700–2000. *Popul Environ* 26(4):343–367.

20. Goldewijk KK, Beusen A, Janssen P (2010) Long-term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1. *The Holocene*.

doi:10.1177/0959683609356587.

21. UDI (2004) *Data base description and research methodology UDI world electric power plants data base* Available at: http://www.platts.com/IM.Platts.Content/downloads/udi/wepp/descmeth.pdf.

22. Flörke M, Bärlund I, Kynast E (2012) Will climate change affect the electricity production sector? A European study. *J Water Clim Change* 3(1):44.

23. Siebert S, et al. (2005) Development and validation of the global map of irrigation areas. *Hydrol Earth Syst Sci Discuss* 2(4): 1299-1327.

24. Siebert S, Hoogeveen J, Frenken K (2006) Irrigation in Africa, Europe and Latin America: Update of the digital global map of irrigation areas to Version 4.

25. Elliott J, et al. (2014) Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proc Natl Acad Sci* 111(9):3239–3244.

26. Siebert S, Döll P, Feick S, Hoogeveen J, Frenken K (2007) Global map of irrigation areas version 4.0. 1. *Johann Wolfgang Goethe Univ Frankf Am Main Ger Agric Organ U N Rome Italy*.

27. Leontief W (1970) Environmental Repercussions and the Economic Structure: An Input-Output Approach. *Rev Econ Stat* 52(3):262–271.

28. Williams ED, Simmons JE, BP (2013) *Water in the energy industry: An introduction* (BP International Limited).

29. Gleick PH (1994) Water and energy. *Annu Rev Energy Environ* 19(1):267–299.

30. Zhang C, Anadon LD (2013) Life Cycle Water Use of Energy Production and Its Environmental Impacts in China. *Environ Sci Technol* 47(24):14459–14467.

31. Royce B, Kaplan E, Garrell M, Geffen TM (1984) Enhanced oil recovery water requirements. *Miner Environ* 6(2):44–53.

32. Wu M, Mintz M, Wang M, Arora S (2009) Water Consumption in the Production of Ethanol and Petroleum Gasoline. *Environ Manage* 44(5):981–997.

33. Mielke E, Anadon LD, Narayanamurti V (2010) Water consumption of energy resource extraction, processing, and conversion. *Belfer Cent Sci Int Aff Harv Kennedy Sch Camb MA U S*. Available at: http://live.belfercenter.org/files/ETIP-DP-2010-15-final-2.pdf [Accessed May 13, 2013].

34. Hoekstra AY, Mekonnen MM (2012) The water footprint of humanity. *Proc Natl Acad Sci* 109(9):3232–3237.

35. IHS Inc (2014) *IHS International Exploration & Production Database* Available at: https://www.ihs.com/pdf/International-Exploration-Production-Database-IHS_165378110913044932.pdf.

36. Suh S (2004) Functions, commodities and environmental impacts in an ecological–economic model. *Ecol Econ* 48(4):451–467.

37. Suh S, Huppes G (2005) Methods for life cycle inventory of a product. *J Clean Prod* 13(7):687–697.

38. Joshi S (1999) Product environmental life-cycle assessment using input-output techniques. *J Ind Ecol* 3(2-3):95–120.

39. Wiedmann TO, et al. (2011) Application of Hybrid Life Cycle Approaches to Emerging Energy Technologies – The Case of Wind Power in the UK. *Environ Sci Technol* 45(13):5900–5907.

40. Clifford P, Richardson S, Hemon D (1989) Assessing the Significance of the Correlation between Two Spatial Processes. *Biometrics* 45(1):123.

41. Osorio F, Vallejos R (2014) *SpatialPack: Package for analysis of spatial data.* Available at: http://cran.r-project.org/package=SpatialPack.

42. R Core Team *R: A language and environment for statistical computing.* (R Foundation for Statistical Computing, Vienna, Austria.) Available at: http://www.R-project.org/.

43. Chenoweth J, Hadjikakou M, Zoumides C (2014) Quantifying the human impact on water resources: a critical review of the water footprint concept. *Hydrol Earth Syst Sci* 18(6):2325–2342.

44. Kounina A, et al. (2012) Review of methods addressing freshwater use in life cycle inventory and impact assessment. *Int J Life Cycle Assess* 18(3):707–721.

45. Daniels PL, Lenzen M, Kenway SJ (2011) The Ins and Outs of Water Use – a Review of Multi-Region Input–Output Analysis and Water Footprints for Regional Sustainability Analysis and Policy. *Econ Syst Res* 23(4):353–370.

46. Feng K, Chapagain A, Suh S, Pfister S, Hubacek K (2011) Comparison of Bottom-up and Top-down Approaches to Calculating the Water Footprints of Nations. *Econ Syst Res* 23(4):371–385.

47. Hoekstra AY (2011) *The water footprint assessment manual: setting the global standard* (Earthscan, London; Washington, DC).

48. Marston L, Konar M, Cai X, Troy TJ (2015) Virtual groundwater transfers from overexploited aquifers in the United States. *Proc Natl Acad Sci* 112(28):8561–8566.

49. Zhao X, et al. (2015) Physical and virtual water transfers for regional water stress alleviation in China. *Proc Natl Acad Sci* 112(4):1031–1035.

50. Lenzen M, et al. (2013) International trade of scarce water. *Ecol Econ* 94:78–85.

51. Spang ES, Moomaw WR, Gallagher KS, Kirshen PH, Marks DH (2014) The water consumption of energy production: an international comparison. *Environ Res Lett* 9(10):105002.

52. Pfister S, Bayer P, Koehler A, Hellweg S (2011) Environmental Impacts of Water Use in Global Crop Production: Hotspots and Trade-Offs with Land Use. *Environ Sci Technol* 45(13):5761–5768.

53. Rijsberman FR (2006) Water scarcity: Fact or fiction? *Agric Water Manag* 80(1–3):5–22.

54. Pfister S, Koehler A, Hellweg S (2009) Assessing the Environmental Impacts of Freshwater Consumption in LCA. *Environ Sci Technol* 43(11):4098–4104.

55. Mubako ST, Lant CL (2013) Agricultural Virtual Water Trade and Water Footprint of U.S. States. *Ann Assoc Am Geogr* 103(2):385–396.

56. Dalin C, Konar M, Hanasaki N, Rinaldo A, Rodriguez-Iturbe I (2012) Evolution of the global virtual water trade network. *Proc Natl Acad Sci* 109(16):5989–5994.

57. Zhang C, Anadon LD (2014) A multi-regional input–output analysis of domestic virtual water trade and provincial water footprint in China. *Ecol Econ* 100:159–172.

58. Feng K, Hubacek K, Pfister S, Yu Y, Sun L (2014) Virtual Scarce Water in China. *Environ Sci Technol* 48(14):7704–7713.

59. Chen Z-M, Chen GQ (2013) Virtual water accounting for the globalized world economy: National water footprint and international virtual water trade. *Ecol Indic* 28:142–149.

60. Biewald A, Rolinski S, Lotze-Campen H, Schmitz C, Dietrich JP (2014) Valuing the impact of trade on local blue water. *Ecol Econ* 101:43–53.

61. Steen-Olsen K, Weinzettel J, Cranston G, Ercin AE, Hertwich EG (2012) Carbon, Land, and Water Footprint Accounts for the European Union: Consumption, Production, and Displacements through International Trade. *Environ Sci Technol* 46(20). doi:10.1021/es301949t.

62. Feng K, Siu YL, Guan D, Hubacek K (2012) Assessing regional virtual water flows and water footprints in the Yellow River Basin, China: A consumption based approach. *Appl Geogr* 32(2):691–701.

63. Wenz L, et al. (2015) Regional and sectoral disaggregation of Multi-region Input-Output tables - A flexible algorithm. *Econ Syst Res* 27(2):194–212.

64. Wilting HC, Faber A, Idenburg AM (2008) Investigating new technologies in a scenario context: description and application of an input–output method. *J Clean Prod* 16(1, Supplement 1):S102–S112.

65. Falkenmark M, Lundqvist J, Widstrand C (1989) Macro-scale water scarcity requires micro-scale approaches. *Nat Resour Forum* 13(4):258–267.

66. Center for International Earth Science Information Network - CIESIN - Columbia University,, Centro Internacional de Agricultura Tropical - CIAT *Gridded Population of the World, Version 3 (GPWv3): Population Density Grid* Available at: http://sedac.ciesin.columbia.edu/data/set/gpw-v3-population-density.

67. Robertson PK, O'Callaghan JF (1986) The Generation of Color Sequences for Univariate and Bivariate Mapping. *IEEE Comput Graph Appl* 6(2):24–32.

68. Vörösmarty CJ, et al. (2010) Global threats to human water security and river biodiversity. *Nature* 467(7315):555–561.

69. Barrett CB, Travis AJ, Dasgupta P (2011) On biodiversity conservation and poverty traps. *Proc Natl Acad Sci* 108(34):13907–13912.

70. Cullis J, O'Regan D (2004) Targeting the water-poor through water poverty mapping. *Water Policy* 6(5):397–411.

71. Sullivan C (2002) Calculating a Water Poverty Index. *World Dev* 30(7):1195–1210.

72. Sullivan CA (2010) Quantifying water vulnerability: a multi-dimensional approach. *Stoch Environ Res Risk Assess* 25(4):627–640.

73. Ohlsson L (2000) Water conflicts and social resource scarcity. *Phys Chem Earth Part B Hydrol Oceans Atmosphere* 25(3):213–220.

74. Sullivan C, Meigh J, Lawrence P (2006) Application of the Water Poverty Index at Different Scales: A Cautionary Tale. *Water Int* 31(3):412–426.

75. Turner WR, et al. (2012) Global Biodiversity Conservation and the Alleviation of Poverty. *BioScience* 62(1):85–92.

76. United Nations Development Programme *Human Development Index dataset.* (http://hdr.undp.org/en/content/human-development-index-hdi).

77. Center for International Earth Science Information Network - CIESIN - Columbia University (2005) Poverty Mapping Project: Global Subnational Prevalence of Child Malnutrition. Available at: http://sedac.ciesin.columbia.edu/data/set/povmap-global-subnational-prevalence-child-malnutrition.

78. Fisher B, Christopher T (2007) Poverty and biodiversity: Measuring the overlap of human poverty and the biodiversity hotspots. *Ecol Econ* 62(1):93–101.

79. Food and Agriculture Organization of the United Nations (2008) *FAO Statistical Yearbook 2007-2008* (FAO).

80. UNICEF, World Bank, WHO (2015) *Joint Malnutrition Dataset* (http://data.unicef.org/nutrition/malnutrition).

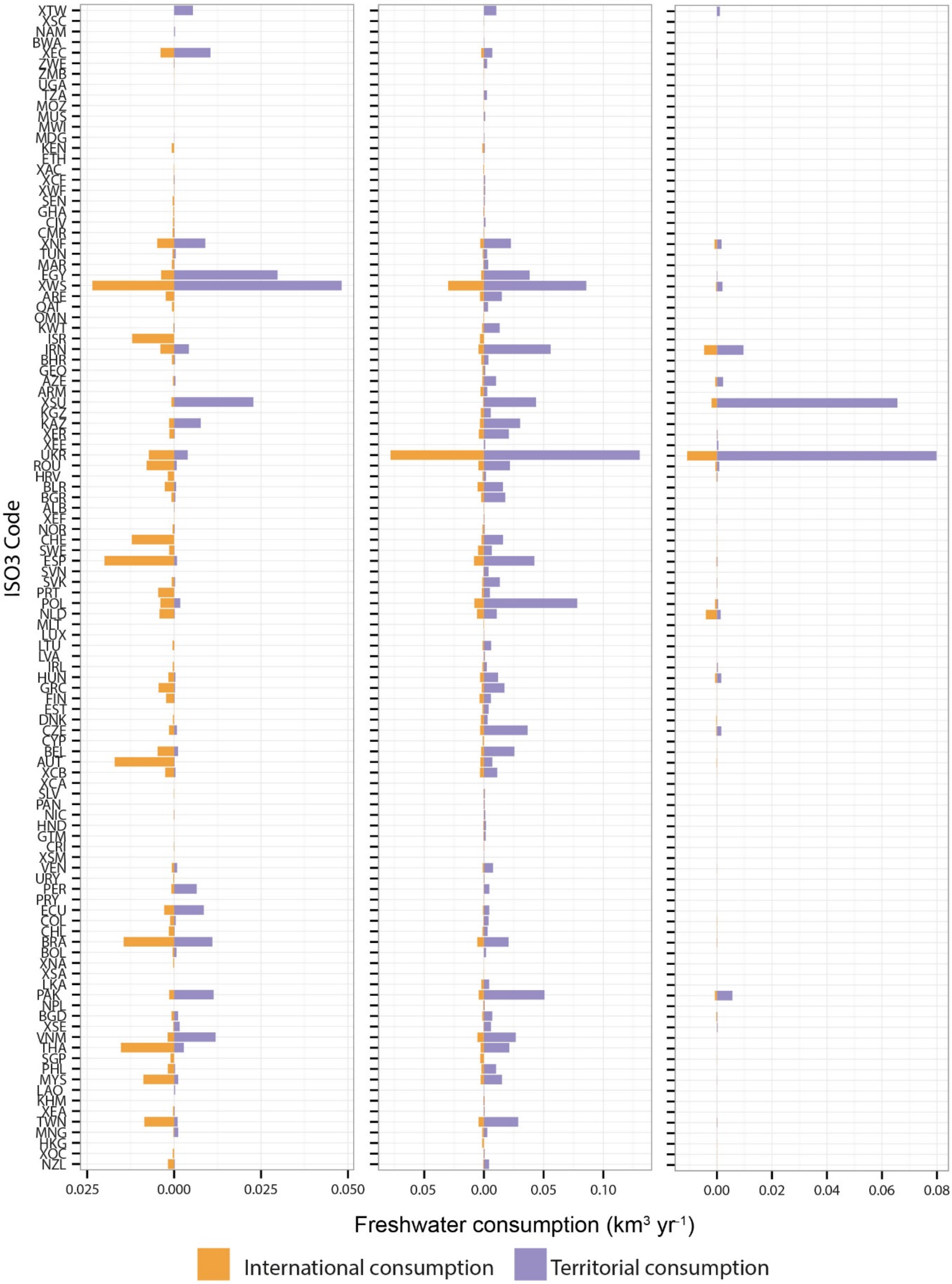

Fig. S1: Territorial and international water consumption associated with (A) petroleum (B) electric and (C) gas sectors for each of the 129 countries/regions analysed using the WaterGAP-MRIO model. Table S2 provides details of the ISO code and county/region that it relates to.

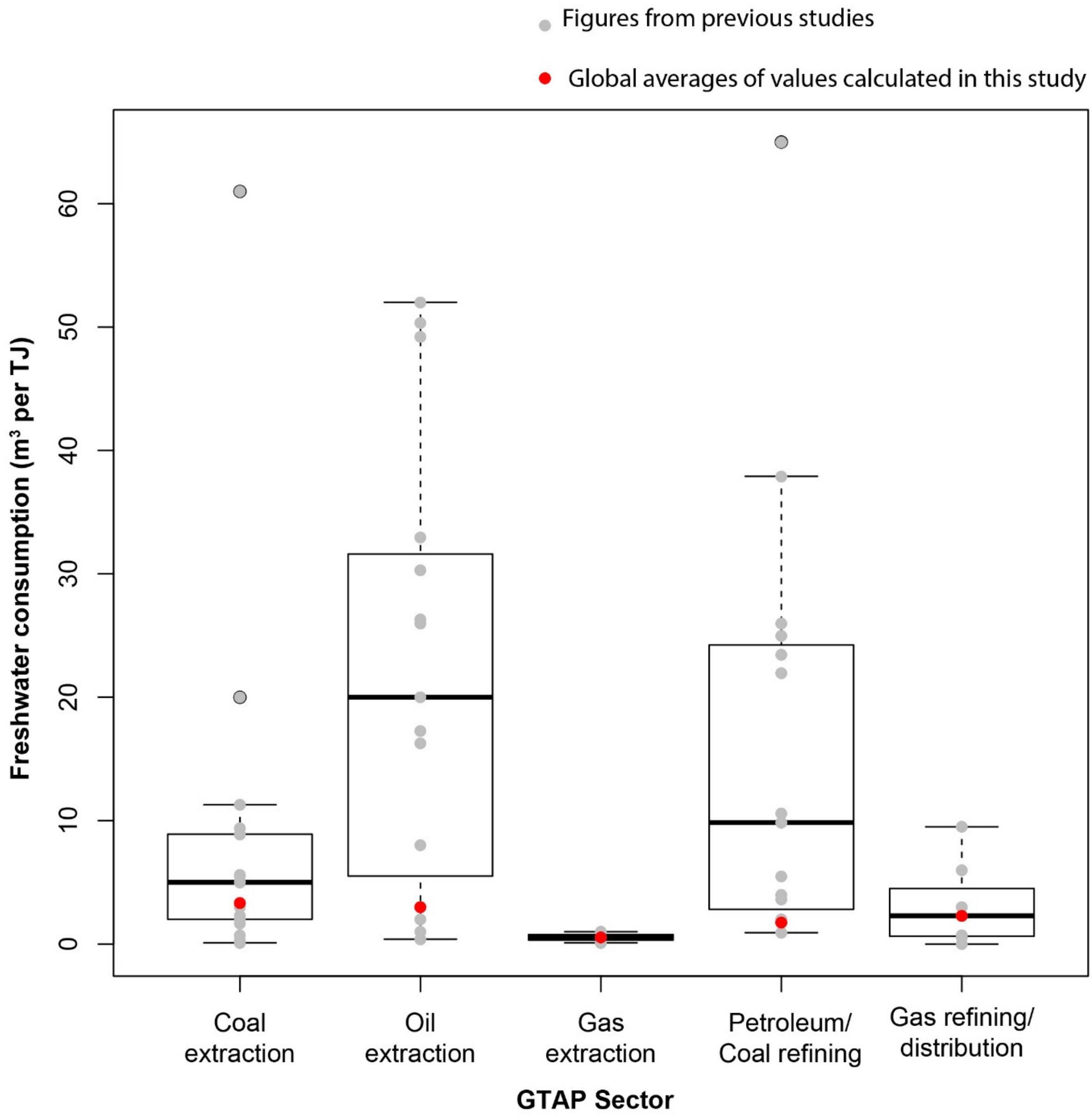

Fig S2: Comparison of values for freshwater consumption per unit energy (m^3 per terajoule) calculated in our model against those derived in previous studies. Grey points indicate values extracted from previous studies and red points indicate global average values calculated from this study.

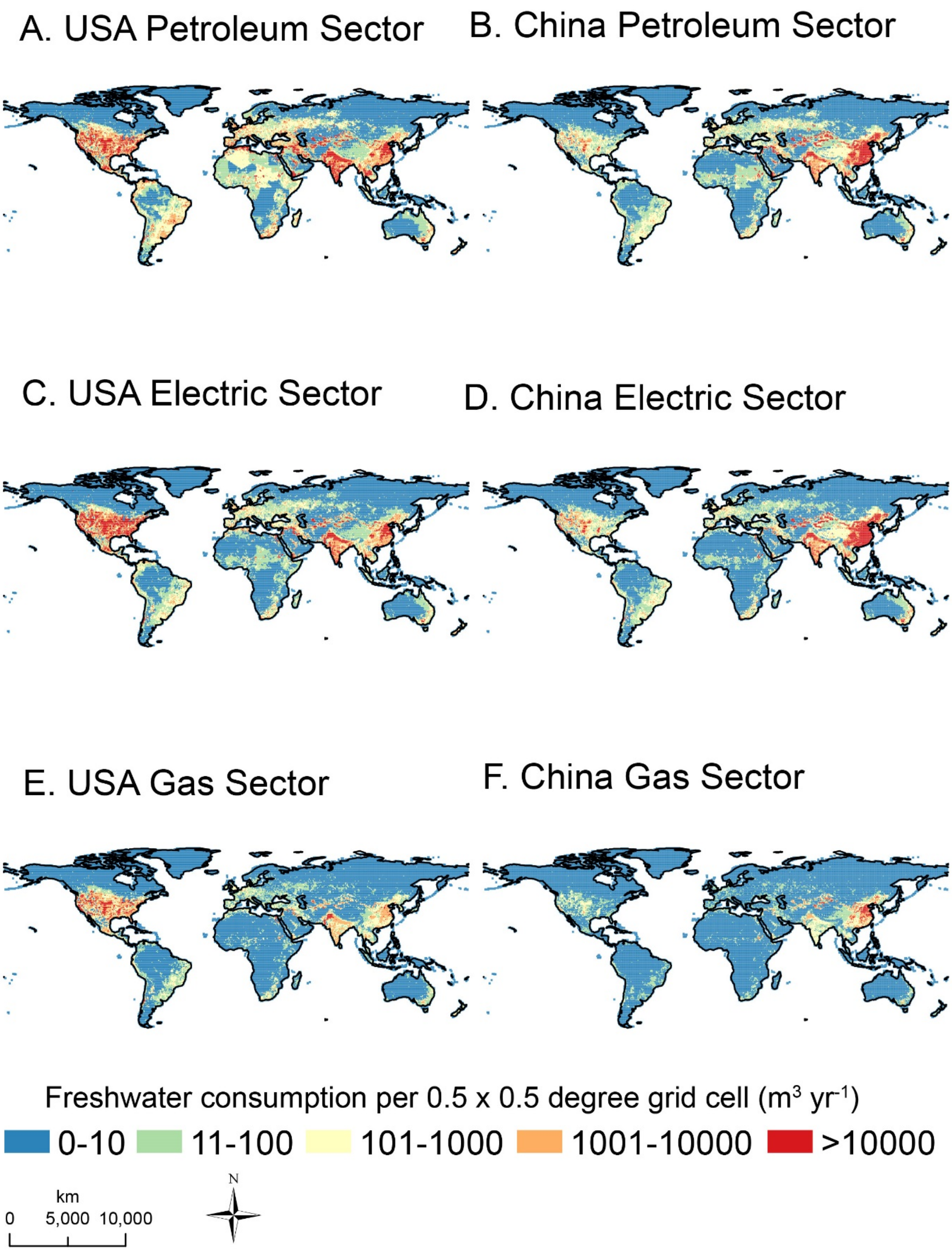

Fig. S3: Spatial pattern of global freshwater consumption driven by freshwater demand from the petroleum sector in the (A) USA and (B) China, for electric sector in (C) the USA and (D) China, and for gas sector in (E) the USA and (F) China. Numbers represent total freshwater consumption (m^3 per yr^{-1}) within each 0.5×0.5 degree grid cell (area approx. 3080 km^2 at the equator).

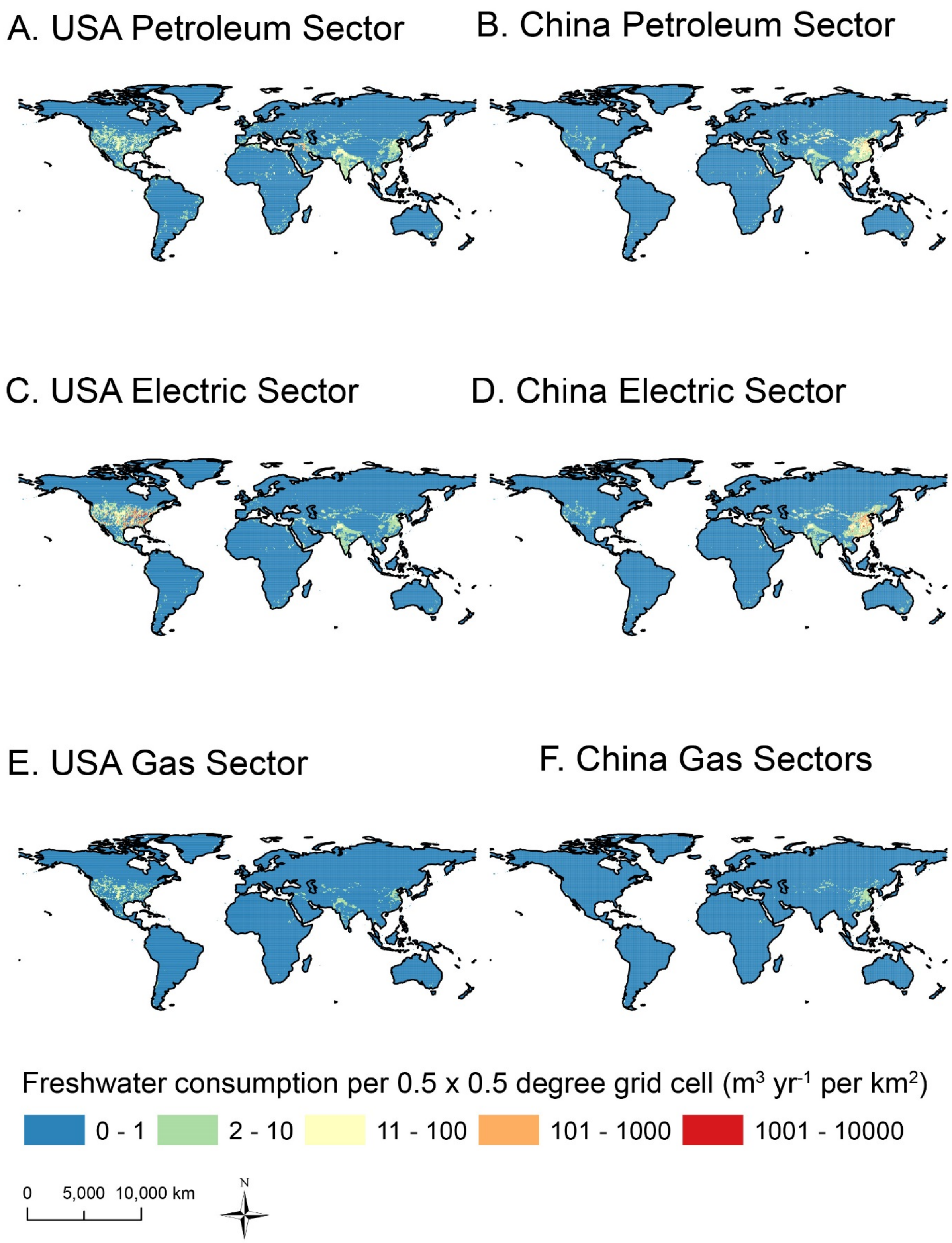

Fig. S4: Spatial pattern of global freshwater consumption driven by freshwater demand from the petroleum sector in the (A) USA and (B) China, for electric sector in (C) the USA and (D) China, and for gas sector in (E) the USA and (F) China. Numbers represent total freshwater consumption within each 0.5 × 0.5 degree grid cell standardised per unit area (m^3 yr^{-1} per km^2).

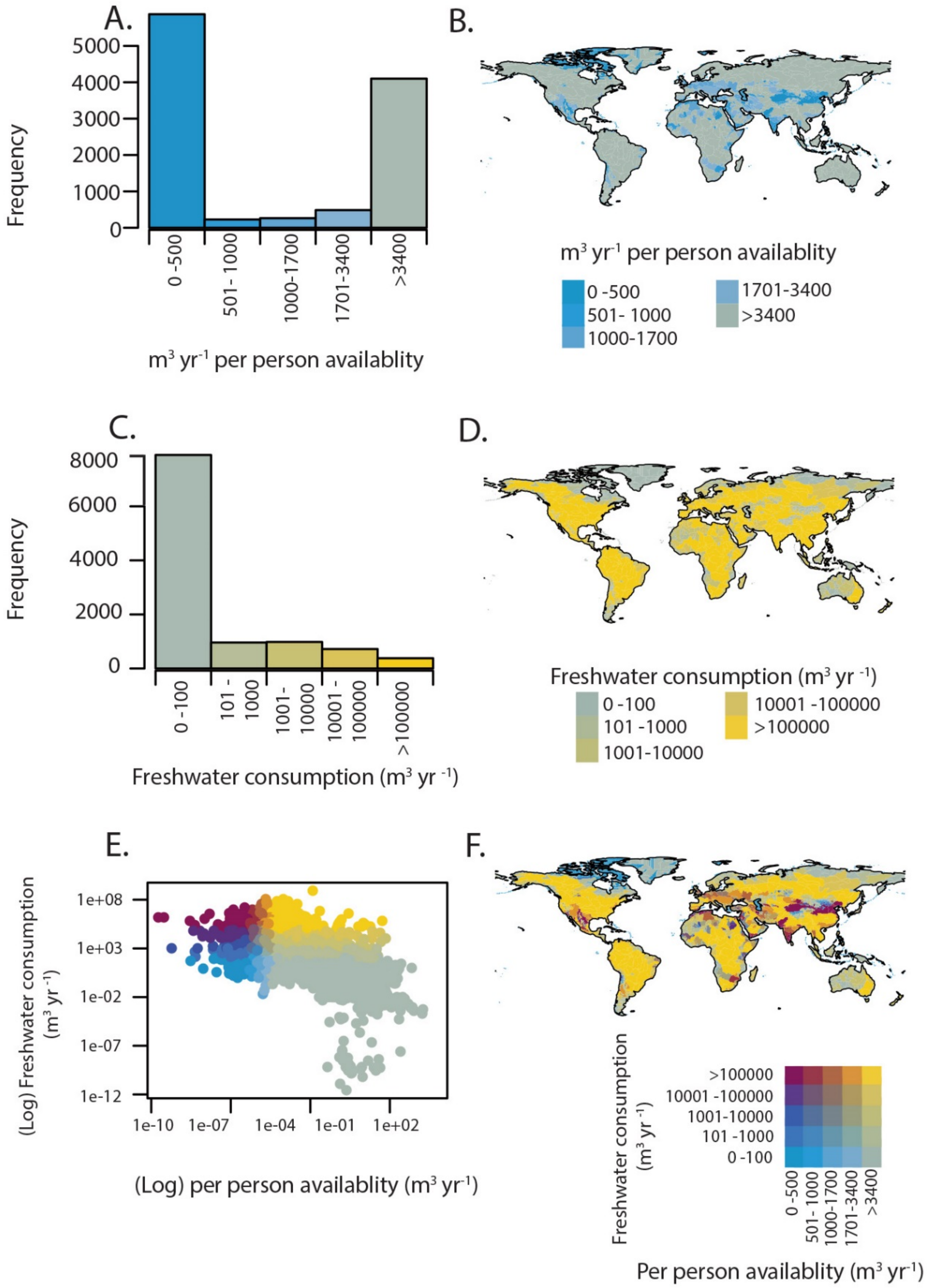

Fig. S5: Relationship between (A; B) per person freshwater availability (m^3 yr^{-1}) within each river basin and (C; D) USA energy sector induced freshwater consumption. Bivariate mapping (E; F) describes the relationship between these two measures with areas in red and purple indicating areas of coincident low per person water availability (m^3 yr^{-1}) and high energy induced freshwater consumption.

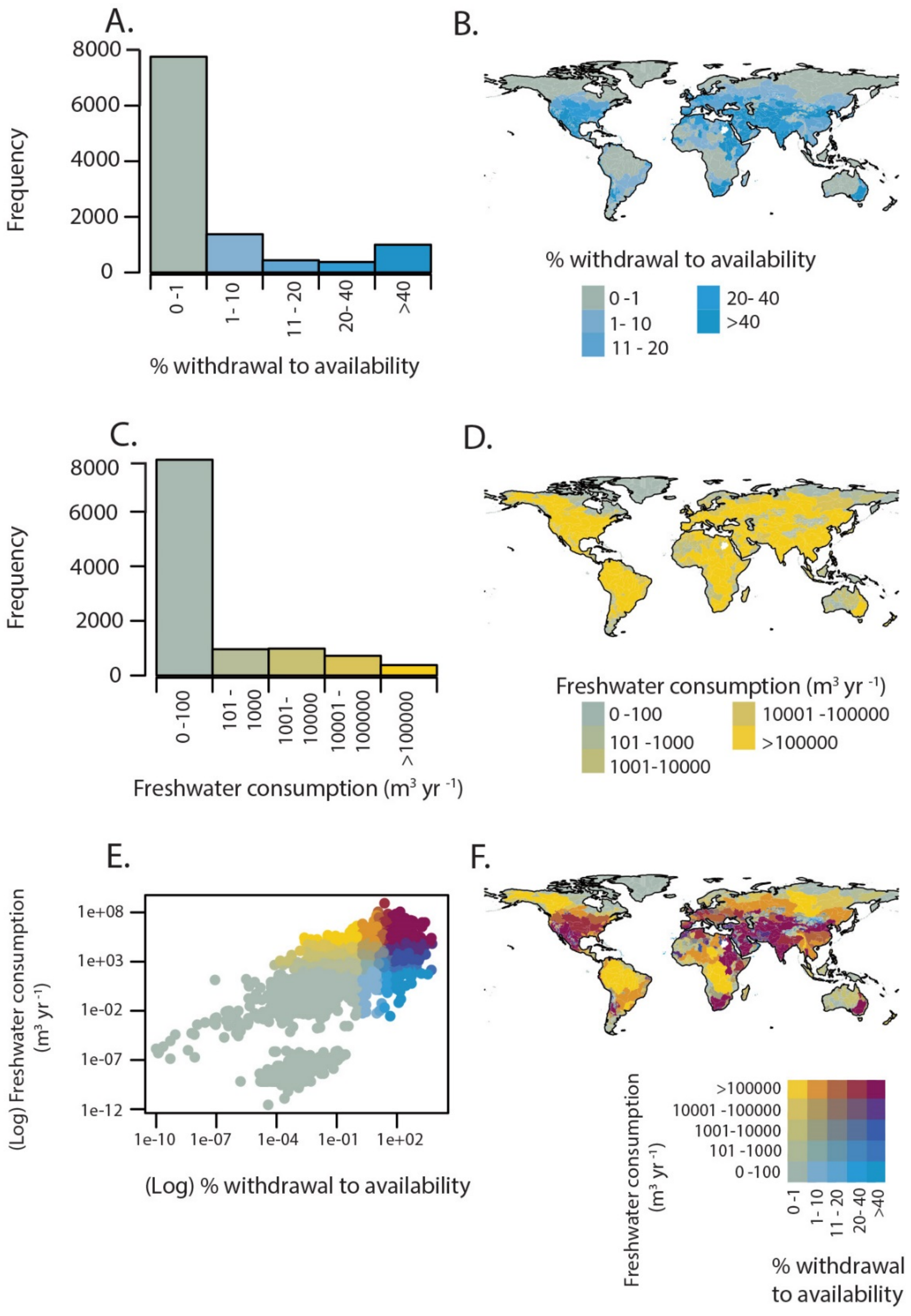

Fig. S6: Relationship between (A; B) the percentage ratio of withdrawal and the available renewable freshwater resource within each river basin and (C; D) USA energy sector induced freshwater consumption. Bivariate mapping (E; F) describes the relationship between these two measures with areas in red and purple indicating areas of coincident high percentage withdrawal to availability and high energy induced freshwater consumption.

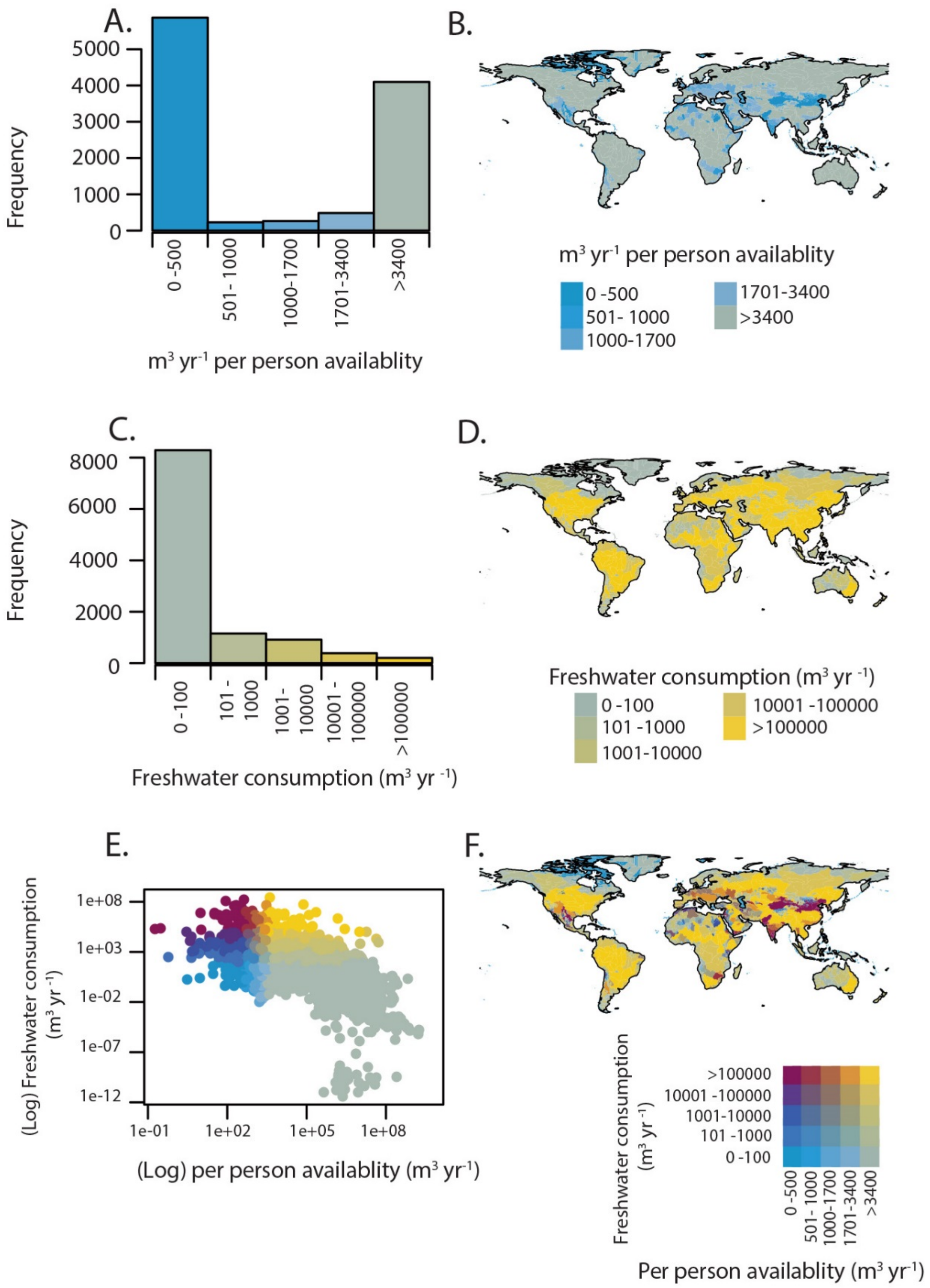

Fig. S7: Relationship between (A; B) per person freshwater availability (m^3 yr^{-1}) within each river basin and (C; D) China energy sector induced freshwater consumption. Bivariate mapping (E; F) describes the relationship between these two measures with areas in red and purple indicating areas of coincident low per person water availability (m^3 yr^{-1}) and high energy induced freshwater consumption.

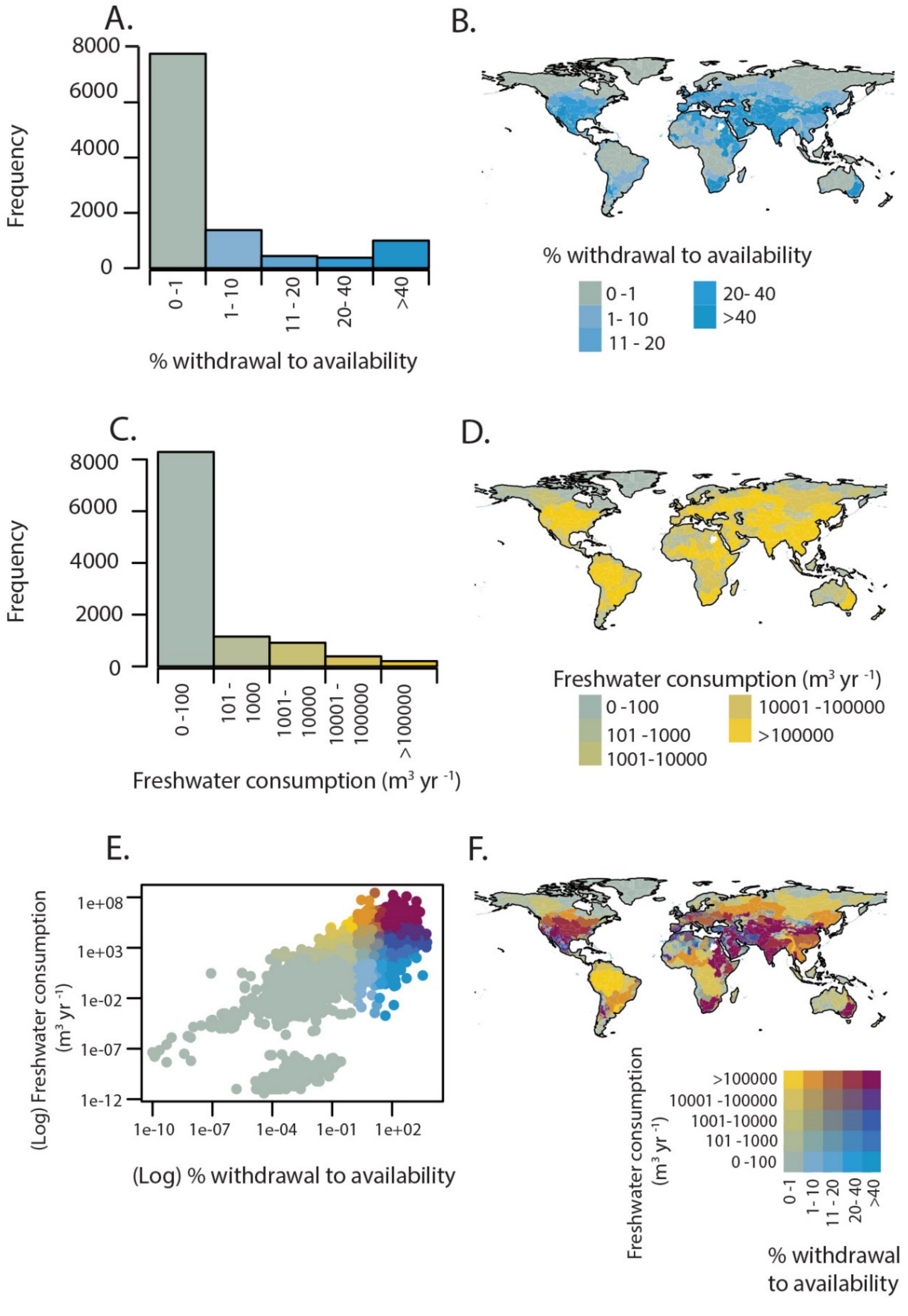

Fig. S8: Relationship between (A; B) the percentage ratio of withdrawal and the available renewable freshwater resource within each river basin and (C; D) China energy sector induced freshwater consumption. Bivariate mapping (E; F) describes the relationship between these two measures with areas in red and purple indicating areas of coincident high percentage withdrawal to availability and high energy induced freshwater consumption.

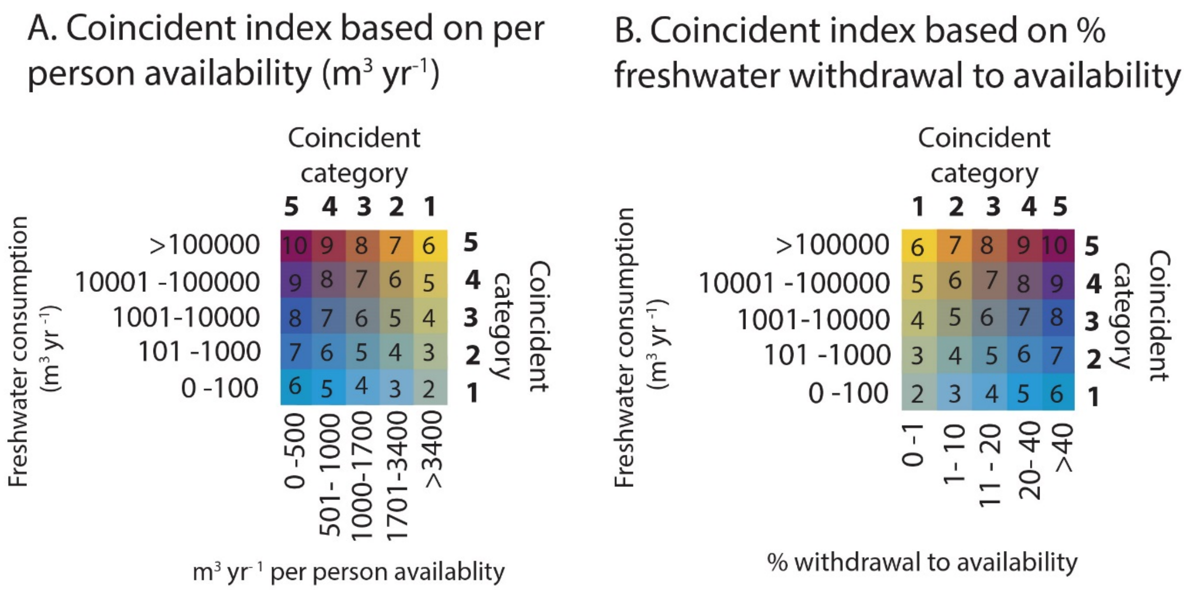

Fig. S9: Calculation of the coincident index based on (A) per person availability and (B) percentage ratio of freshwater withdrawal to availability. Data is taken from the bivariate mapping (Fig. S5-8) and each measure assigned a score from low (one) to high (five). The combined score based on the two dimensions (freshwater scarcity + freshwater consumption induced by energy sectors) produces a coincident index of spatial overlap.

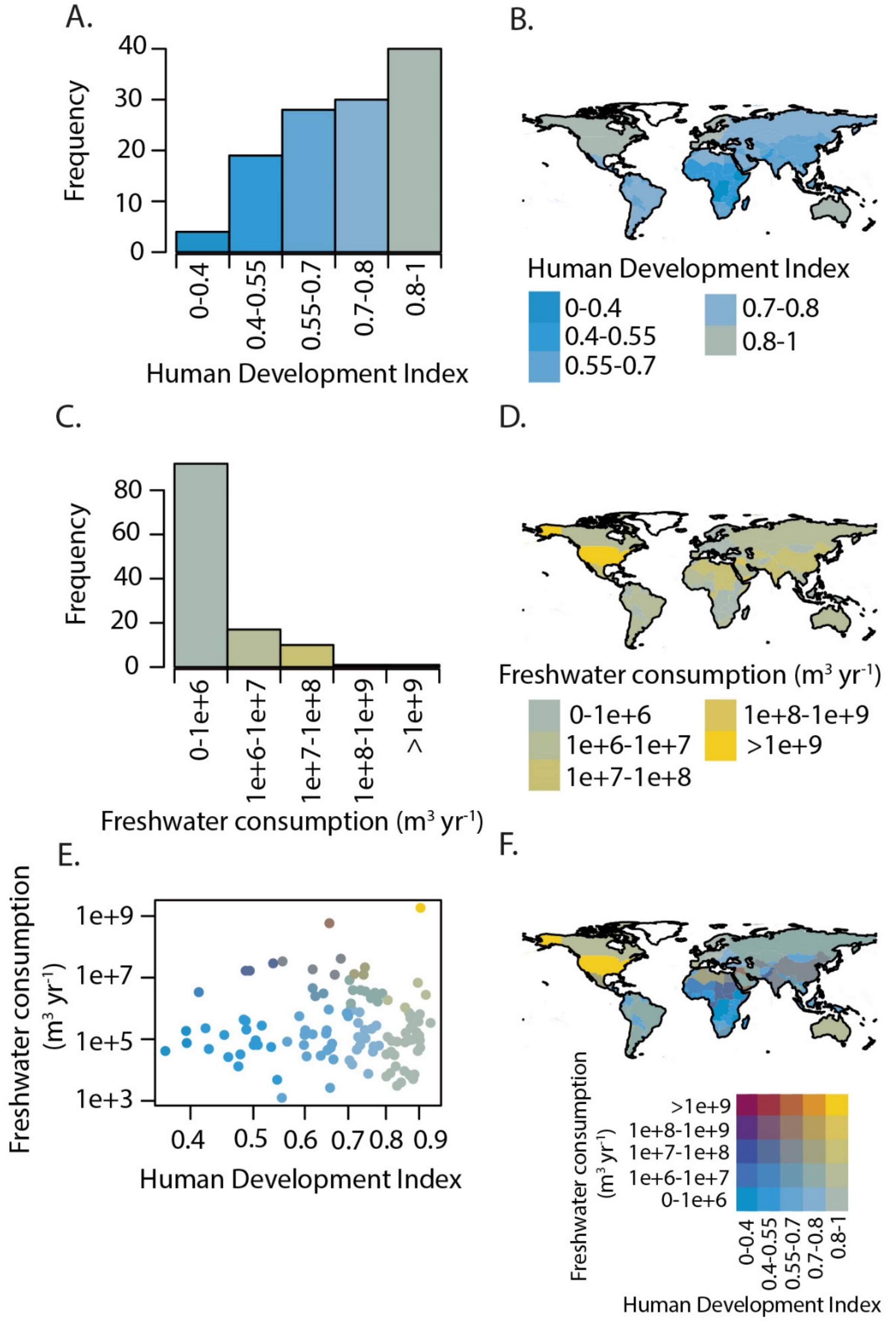

Fig. S10: Relationship between (A; B) the Human Development Index in 2008 taken as an indicator of social adaptive capacity for each GTAP country/region, and (C; D) USA energy sector induced freshwater consumption. Bivariate mapping (E; F) describes the relationship between these two measures with countries/regions in red and purple indicating areas of coincident low capacity to adapt to freshwater scarcity and high energy induced freshwater consumption.

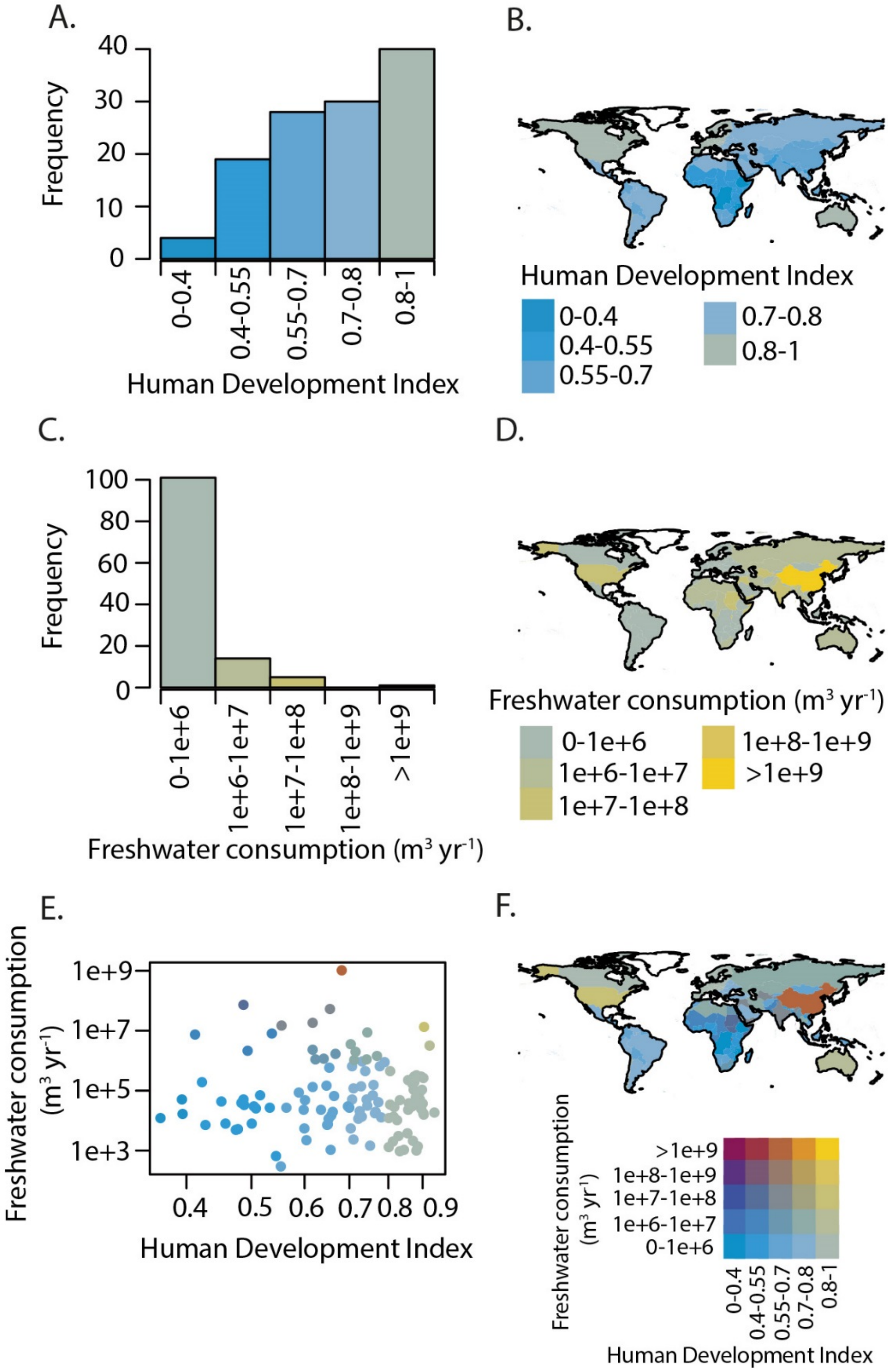

Fig S11: Relationship between (A; B) the Human Development Index in 2008 taken as an indicator of social adaptive capacity for each GTAP country/region, and (C; D) China energy sector induced freshwater consumption. Bivariate mapping (E; F) describes the relationship between these two measures with countries/regions in red and purple indicating areas of coincident low capacity to adapt to freshwater scarcity and high energy induced freshwater consumption.

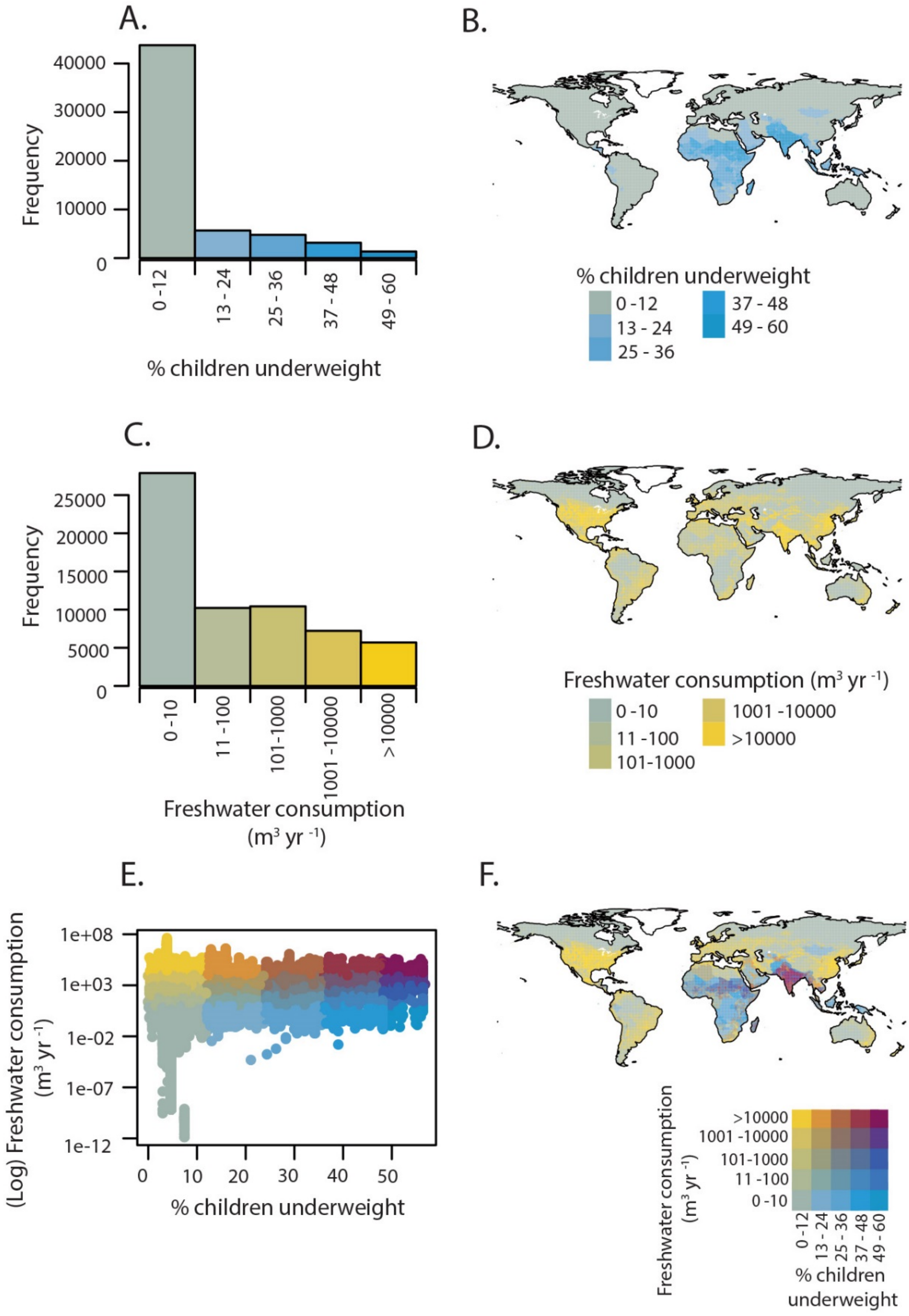

Fig. S12: Relationship between (A; B) the prevalence of child malnutrition per 0.5 × 0.5 degree grid cell taken as a proxy for capacity to adapt to freshwater scarcity, and (C; D) USA energy sector induced freshwater consumption. Bivariate mapping (E; F) describes the relationship between these two measures with areas in red and purple indicating areas of coincident low capacity to adapt to freshwater scarcity and high energy induced freshwater consumption.

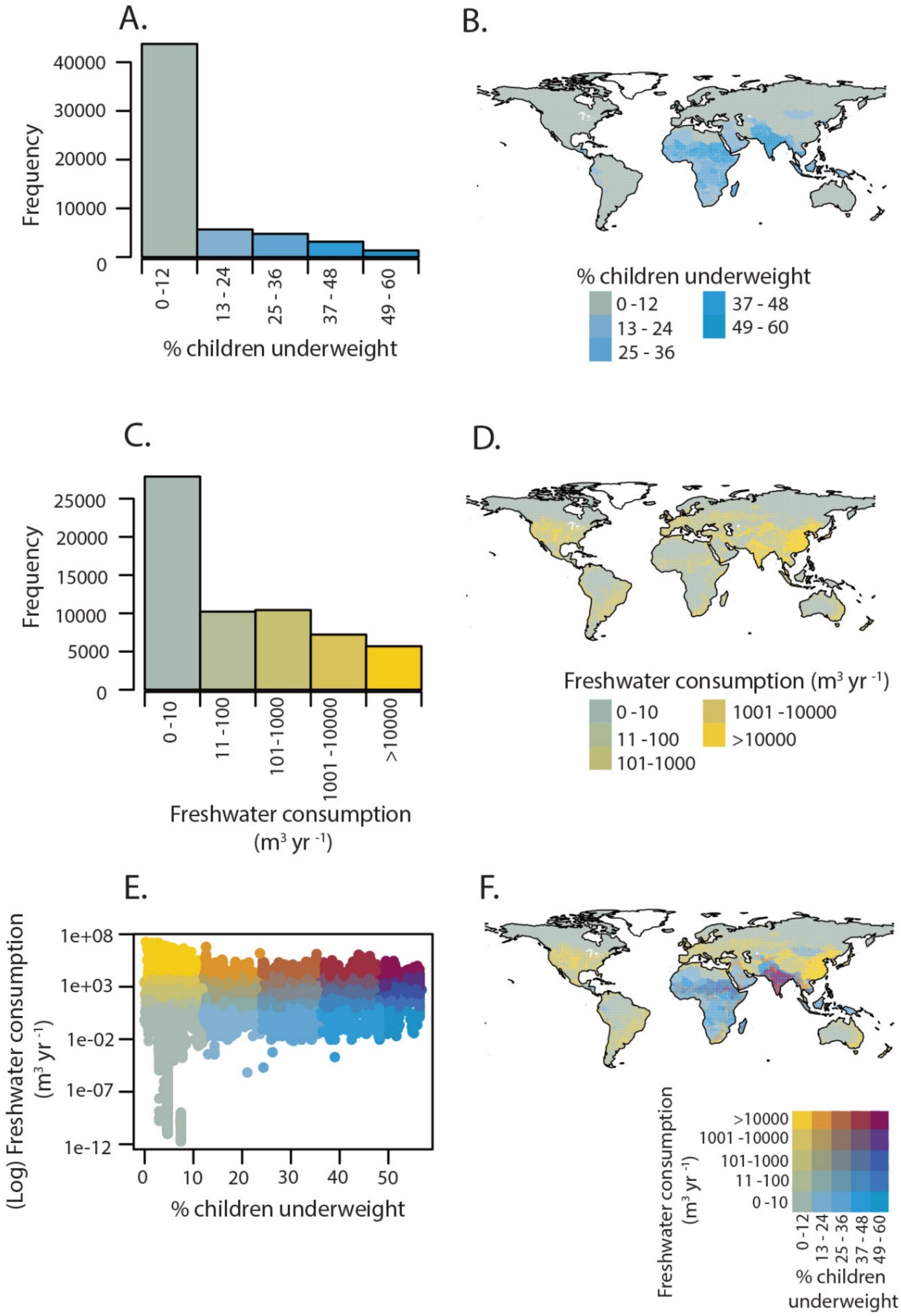

Fig. S13: Relationship between (A; B) the prevalence of child malnutrition per 0.5 × 0.5 degree grid cell taken as a proxy for capacity to adapt to freshwater scarcity, and (C; D) China energy sector induced freshwater consumption. Bivariate mapping (E; F) describes the relationship between these two measures with areas in red and purple indicating areas of coincident low capacity to adapt to freshwater scarcity and high energy induced freshwater consumption.

Table S1: Fifty seven economic sectors described by the GTAP database indicating the sectors groupings used in the representation of water consumption in Fig. 2 main text.

GTAP Sector	**Sector grouping used in Fig. 2**
Paddy rice	Crop
Wheat	Crop
Cereal grains nec	Crop
Vegetables, fruit, nuts	Crop
Oil seeds	Crop
Sugar cane, sugar beet	Crop
Plant-based fibers	Crop
Crops nec	Crop
Cattle,sheep,goats,horses	Livestock
Animal products nec	Livestock
Raw milk	Livestock
Wool, silk-worm cocoons	Livestock
Forestry	Crop
Fishing	Livestock
Coal	Petroleum/coal
Oil	Petroleum/coal
Gas	Gas
Minerals nec	Manufacturing
Meat: cattle,sheep,goats,horse	Manufacturing
Meat products nec	Manufacturing
Vegetable oils and fats	Manufacturing
Dairy products	Manufacturing
Processed rice	Manufacturing
Sugar	Manufacturing
Food products nec	Manufacturing
Beverages and tobacco products	Manufacturing
Textiles	Manufacturing
Wearing apparel	Manufacturing
Leather products	Manufacturing
Wood products	Manufacturing
Paper products, publishing	Manufacturing
Petroleum, coal products	Petroleum/coal
Chemical,rubber,plastic prods	Manufacturing
Mineral products nec	Manufacturing
Ferrous metals	Manufacturing
Metals nec	Manufacturing
Metal products	Manufacturing
Motor vehicles and parts	Manufacturing
Transport equipment nec	Manufacturing
Electronic equipment	Manufacturing
Machinery and equipment nec	Manufacturing
Manufactures nec	Manufacturing

Electricity	Electricity
Gas manufacture, distribution	Gas
Water	Water
Construction	Supporting
Trade	Supporting
Transport nec	Supporting
Sea transport	Supporting
Air transport	Supporting
Communication	Supporting
Financial services nec	Supporting
Insurance	Supporting
Business services nec	Supporting
Recreation and other services	Supporting
PubAdmin/Defence/Health/Educat	Supporting
Dwellings	Domestic

Table S2: Representation of the 129 countries used by the GTAP database indicating their standard ISO 3 code, the broad economic grouping used in selection of the subset of countries in Fig. 1 of the main text and Fig. S1 of the SOM, and their grouping by UN macro geographic region used in Fig. 2 of the main text.

GTAP Country/region	**ISO 3 Code**	***Region in Fig. 2***	***Economic group in Fig. 1***
Australia	AUS	Oceania	G20
New Zealand	NZL	Oceania	
Rest of Oceania	XOC	Oceania	
China	CHN	**China***	G20, BRIC
Hong Kong	HKG	Asia	
Japan	JPN	Asia	G20
Republic of Korea	KOR	Asia	G20
Mongolia	MNG	Asia	
Taiwan	TWN	Asia	
Rest of East Asia	XEA	Asia	
Cambodia	KHM	Asia	
Indonesia	IDN	Asia	G20, MINT
Lao People's Democratic Republic	LAO	Asia	
Malaysia	MYS	Asia	
Philippines	PHL	Asia	
Singapore	SGP	Asia	
Thailand	THA	Asia	
Viet Nam	VNM	Asia	
Rest of Southeast Asia	XSE	Asia	
Bangladesh	BGD	Asia	
India	IND	Asia	G20, BRIC

Nepal	NPL	Asia	
Pakistan	PAK	Asia	
Sri Lanka	LKA	Asia	
Rest of South Asia	XSA	Asia	
Canada	CAN	Americas	G20
United States of America	USA	**USA***	G20 G20, MINT
Mexico	MEX	Americas	G20, MINT
Rest of North America	XNA	Americas	
Argentina	ARG	Americas	G20
Plurinational Republic of Bolivia	BOL	Americas	
Brazil	BRA	Americas	
Chile	CHL	Americas	
Colombia	COL	Americas	
Ecuador	ECU	Americas	
Paraguay	PRY	Americas	
Peru	PER	Americas	
Uruguay	URY	Americas	
Venezuela	VEN	Americas	
Rest of South America	XSM	Americas	
Costa Rica	CRI	Americas	
Guatemala	GTM	Americas	
Honduras	HND	Americas	
Nicaragua	NIC	Americas	
Panama	PAN	Americas	
El Salvador	SLV	Americas	
Rest of Central America	XCA	Americas	
Caribbean	XCB	Americas	
Austria	AUT	Europe	
Belgium	BEL	Europe	
Cyprus	CYP	Europe	
Czech Republic	CZE	Europe	
Denmark	DNK	Europe	
Estonia	EST	Europe	
Finland	FIN	Europe	
France	FRA	Europe	G20
Germany	DEU	Europe	G20
Greece	GRC	Europe	
Hungary	HUN	Europe	
Ireland	IRL	Europe	
Italy	ITA	Europe	G20
Latvia	LVA	Europe	
Lithuania	LTU	Europe	
Luxembourg	LUX	Europe	
Malta	MLT	Europe	

Netherlands	NLD	Europe	
Poland	POL	Europe	
Portugal	PRT	Europe	
Slovakia	SVK	Europe	
Slovenia	SVN	Europe	
Spain	ESP	Europe	
Sweden	SWE	Europe	
United Kingdom	GBR	Europe	G20
Switzerland	CHE	Europe	
Norway	NOR	Europe	
Rest of EFTA	XEF	Europe	
Albania	ALB	Europe	
Bulgaria	BGR	Europe	
Belarus	BLR	Europe	
Croatia	HRV	Europe	
Romania	ROU	Europe	
Russian Federation	RUS	Europe	G20, BRIC
Ukraine	UKR	Europe	
Rest of Eastern Europe	XEE	Europe	
Rest of Europe	XER	Europe	
Kazakhstan	KAZ	Asia	
Kyrgyzstan	KGZ	Asia	
Rest of Former Soviet Union	XSU	Asia	
Armenia	ARM	Asia	
Azerbaijan	AZE	Asia	
Georgia	GEO	Asia	
Bahrain	BHR	Asia	
Iran Islamic Republic of	IRN	Asia	
Israel	ISR	Asia	
Kuwait	KWT	Asia	
Oman	OMN	Asia	
Qatar	QAT	Asia	
Saudi Arabia	SAU	Asia	G20
Turkey	TUR	Asia	G20, MINT
United Arab Emirates	ARE	Asia	
Rest of Western Asia	XWS	Asia	
Egypt	EGY	Africa	
Morocco	MAR	Africa	
Tunisia	TUN	Africa	
Rest of North Africa	XNF	Africa	
Cameroon	CMR	Africa	
Cote d'Ivoire	CIV	Africa	
Ghana	GHA	Africa	
Nigeria	NGA	Africa	MINT

Senegal	SEN	Africa	
Rest of Western Africa	XWF	Asia	
Central Africa	XCF	Africa	
South Central Africa	XAC	Africa	
Ethiopia	ETH	Africa	
Kenya	KEN	Africa	
Madagascar	MDG	Africa	
Malawi	MWI	Africa	
Mauritius	MUS	Africa	
Mozambique	MOZ	Africa	
Tanzania United Republic of	TZA	Africa	
Uganda	UGA	Africa	
Zambia	ZMB	Africa	
Zimbabwe	ZWE	Africa	
Rest of Eastern Africa	XEC	Africa	
Botswana	BWA	Africa	
Namibia	NAM	Africa	
South Africa	ZAF	Africa	G20
Rest of South African Customs Union	XSC	Africa	
Rest of the World	XTW	Africa	

Table S3: Proportion contribution of each of the aggregate economic sectors to the 1314 km^3 of global annual freshwater consumption represented in the WaterGAP model. These figures represent freshwater consumption before EE-MRIO re-attributes to the sectors where final demand resides.

Aggregate GTAP Sector	Total renewable freshwater consumption in WaterGAP (km^3 yr^{-1})	% Total renewable freshwater consumption in WaterGAP
Crop	1207.61	91.85
Livestock	29.78	2.26
Manufacturing	25.43	1.93
Supporting	27.84	2.12
Domestic	0.55	0.04
Water	5.12	0.39
Petroleum/coal	1.30	0.10
Gas	0.34	0.03
Electric	16.74	1.27

Table S4: Proportion contribution of geographic regions to the 1314 km^3 of global annual freshwater consumption represented in the WaterGAP model.

Region	Total renewable freshwater consumption in WaterGAP (km^3 yr^{-1})	% Total renewable freshwater consumption in WaterGAP
USA*	392.51	9.47
China*	387.35	9.35
Africa	342.41	8.27
Americas	311.58	7.52
Asia	2416.58	58.33
Europe	253.41	6.12
Oceania	38.89	0.94

Table S5: Cross mapping between the crop and livestock sectors of WaterGAP (rows) and GTAP (columns). The abbreviation nec indicates products “not elsewhere classified”.

	GTAP Category									
WaterGAP Category	Paddy rice	Wheat	Cereal grains nec	Vegetables, fruit, nuts	Oil seeds	Sugar cane, sugar beet	Plant-based fibers	Crops nec	Cattle, sheep, goats, horses	Animal products nec
Rice	1									
Wheat		1								
Winter wheat		1								
Barley			1							
Cotton							1			
Fodder								1		
Maize			1							
Potato				1						
Sugarbeet						1				
Sunflower					1					
Vegetable				1						
Millet/ Sorghum								1		
Pulses								1		
Soy					1					
Olives					1					
Fruits				1						
Sugarcane						1				
Coffee								1		
Tobacco								1		
Dairy cattle									1	
Non-dairy cattle									1	
Pig										1
Sheep									1	
Goats									1	
Buffaloes									1	
Camels									1	
Horses									1	
Chicken										1
Turkeys										1
Ducks										1
Geese										1

Table S6: Correlations between freshwater consumption associated with all three energy for the USA and China. Absolute differences in freshwater consumption are assessed using Wilcoxon signed rank test where V corresponds to the sum of ranks assigned to the differences with positive sign.

	Correlation test				**Wilcoxon signed rank test**	
Comparison	r	Fstat	Degrees of Freedom	pvalue	V	pvalue
All energy sectors	0.98	2920.93	120	<0.001	219437248	<0.001
Petroleum	0.98	2776.78	110	<0.001	403119013	<0.001
Electric	0.98	3727.88	135	<0.001	188439552	<0.001
Gas	0.98	3149.49	129	<0.001	1134823275	<0.001